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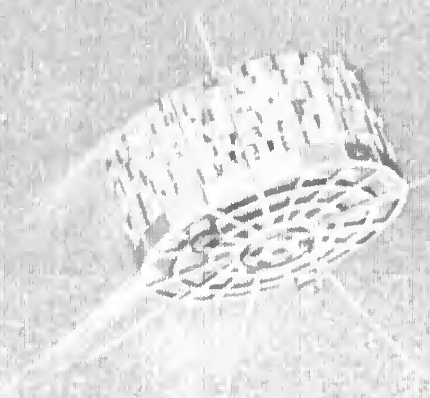
PRACTICAL INTERPRETATION OF METEOROLOGICAL SATELLITE DATA

WILLIAM K. WIDGER, JR.

PAUL E. SHERR

C. W. C. ROGERS



ARACON GEOPHYSICS CO.
CONCORD, MASSACHUSETTS
A DIVISION OF ALLIED RESEARCH ASSOCIATES, INC.

CONTRACT NO. AF 19(628)-2471
PROJECT NO. 6698
TASK NO. 669802

SEPTEMBER 1964

FINAL REPORT

PREPARED FOR

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

ERRATA SHEET

FOR

PRACTICAL INTERPRETATION OF METEOROLOGICAL SATELLITE DATA

(Final Report, Contract No. AF 19(628)-2471)

9 December 1964

<u>Page 134, Fig. 8-1</u>

Add to caption: "Lake Michigan has been outlined to provide a geographical reference in the TIROS picture."

<u>Page 151, Fig. 8-14</u>

Add to caption: "The arrows in this and the next three figures show the wind direction."

<u>Page 186, Fig. 10-3</u>

As reads: "C" at 52^{o}N, 82^{o}W, should read: "<u>+C</u>"

<u>Page 210, Section 10.4.4.2, Line 2</u>

As reads: "...near 30N, 50W." should read: "...near <u>40N</u>, 50W."

<u>Page 258, Fig. 11-35</u>

As reads: "...Typhoon Ruch...", should read: "...Typhoon <u>Ruth</u>..."

<u>Page 287, Line 3</u>

Delete comma after "...fit..."

<u>Page 297, Fig. 13-1, and Page 298, Fig. 13-2</u>

Change "T_E" to "T_r"

<u>Page 303, Section 13.3.2, Line 1</u>

Change superscript references from "39, 91" to "39, <u>131</u>"

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Satellite Cloud Patterns Can Aid the Air Weather Service Forecaster in Determining the Location and Characteristics of Major Weather Systems

AFCRL-64-807

9219-12

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FOREWORD

The purpose of this report is to illustrate meso- and synoptic-scale cloud features and patterns as seen from satellites, and to evaluate methods of analyzing and exploiting meteorological satellite data for operational applications. Applicable methods are presented in forms suitable for use and reference by operational meteorologists. While this report relies heavily on already published material, it also presents techniques newly developed by ARACON Geophysics Company which may significantly aid the forecaster when applying meteorological satellite data in synoptic analyses.

The material presented herein draws very extensively on the results of previous research and development as published in the technical literature and in available technical reports through early 1964. Every attempt is made to appropriately credit these sources through use of superscript numerals keyed to the associated list of over 130 References which will be found at the end of the main body of the report. In a departure from common scientific practice, the names of the authors cited are seldom given in the text since they are rarely of direct concern to the operational and field meteorologists for whom the report has primarily been written; the authors' names are of course included in the References.

In many cases, it has appeared desirable or been convenient to utilize wording directly extracted from the cited sources, subject to a greater or lesser degree of editing to fit the specific objectives of this report. On the other hand, it has seemed desirable to omit frequent use of quotation marks, parentheses, brackets, and multiple dashes since they would only impede the train of thought of the intended reader---particularly in those sections where the editing has been extensive and the common notations of partial quotation would necessarily need to be included, if at all, in excessive numbers. It is hoped that those whose words were so used will understand the reasons for so doing and will be forgiving of this breach of normal scientific and literary etiquette. The authors of this report hereby acknowledge their considerable debt to those whose works and words they used; all credit for such material belongs to the original authors as cited. On the other hand, the authors of this report accept full responsibility for any errors or misuses of extracted material that have resulted from the editing modifications made when incorporating the words of others in this report.

The authors are furthermore and directly obligated to:

Dr. Carl W. Kreitzberg, Mr. John H. Conover, and their colleagues of the Satellite Meteorology Branch of the Air Force Cambridge Research Laboratories for their many valuable suggestions and other assistance during the preparation of this report.

Lt. Col. James B. Jones, former Air Weather Service member, National Weather Satellite Center, for providing the information included in Appendix A, and reproducible copies of Major Miller's paper as reprinted in Appendix B.

Drs. Arnold H. Glaser and Raymond Wexler, and Messrs. Roland J. Boucher, Earl S. Merritt, and Robert W. White of ARACON Geophysics Company for their many and most helpful criticisms and suggestions during the preparation of this report.

Credits for individual sections of this report are primarily attributable as follows:

Mr. Earl S. Merritt:	Section 11.12
Mr. C. W. C. Rogers:	Section 6.2.3.1; Selection and Integration of Figures.
Mr. Paul E. Sherr:	Chapters 3, 10; Sections 6.7, 13.3, 13.4
Dr. William K. Widger, Jr.:	Chapters 1, 2, 4, 5, 6, 7, 8, 9, 11, 12 Appendixes C, D, E, F Sections 10.5, 13.1, 13.2

ABSTRACT

This report attempts to consolidate within a single document information pertinent to the operational interpretation, as regards weather analysis and forecasting, of meteorological satellite data. Accordingly, it extracts, integrates, and summarizes material available in the literature and in technical reports up through early 1964. The report is written specifically for the use of Air Weather Service field forecasters.

Topics considered include the coverage, scale, and resolution of the satellite data, operationally available data formats, coordination with other meteorological data, cloud type interpretation, key features observed in the pictures, extratropical vortex interpretations, other synoptic and mesoscale features, interpretations of tropical data, and contributions of the satellite data to weather forecasting.

Procedures for the integration of satellite and conventional data and analyses, and for the use of satellite data to provide improved synoptic analyses, are developed and presented.

Guidance as regards the operational interpretation, application, and value of infrared data for atmospheric windows is provided, looking toward the time when such data are made available to the field forecaster.

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CHAPTER 1

INTRODUCTION

Although TIROS was originally intended as primarily a research and development satellite, within a few days of the first launch nephanalyses based on the TIROS data were being distributed by facsimile for the operational use of Air Force meteorologists. The use that could then be made of these data was limited by lack of knowledge of how best to interpret the observed cloud patterns. While many problems of interpretation still exist, over the past four years much has been learned as a result both of operational experience and of numerous basic and applied research programs.

From the viewpoint of the Air Weather Service forecaster, much of this information has not been readily available, since it is scattered through a number of different scientific journals. In many cases, it exists only in technical reports of limited distribution. Even that material which is available is too often only in the form of case studies, with little or no discussion of the applicability to other situations.

The purpose of this report is to summarize and integrate presently available information which could be of use to Air Weather Service personnel in the application of data from TIROS and subsequent meteorological satellites. Since these personnel are variously assigned to Weather Centrals or to weather detachments at operational Air Force installations, satellite information is available to them in several different forms or combinations of forms. Facsimile transmitted nephanalyses should be available in almost all cases, whereas only relatively few locations have direct access to the cloud pictures, either through an Automatic Picture Transmission (APT) facility or facsimile transmissions of selected significant pictures. This report attempts to take into account these differences in available information. The discussions of what can and cannot be seen in the pictures should be helpful, even to those receiving only the nephanalyses, by providing information as to the limitations of the data on which the nephs are based.

It is the central theme of this report that the weather satellite provides simply another operational tool to be used in the preparation of more precise synoptic analyses, and that the satellite observations should not be considered as unique and uncorrelated data (except where no other data exists). To this end, the need for marrying the satellite data to the conventional data will be discussed in Chapter 3 with more specific techniques and examples provided in Chapter 10.

Chapter 2 of this report discusses some inherent limitations to the data: coverage limitations imposed by orbital factors; resolution and contrast limitations deriving from the cameras used; presentations as limited by available weather communications facilities. Chapter 3 not only emphasizes the importance of integrating satellite data with all available conventional data, but also treats general aspects of various situations of relative data availability. Chapter 4 provides information on cloud type interpretation. In Chapter 5, the key cloud features visible in satellite photographs are summarized as a prelude to more extensive discussions in subsequent sections. Chapters 6 and 7 discuss extra-tropical vortices and other extra-tropical synoptic features. Mesoscale features are examined in Chapter 8, while Chapter 9 treats surface and marine phenomena seen in the pictures. Techniques for using and integrating satellite data in routine weather analyses are described in Chapter 10, and illustrated with several case studies.

Chapter 11 examines tropical systems as seen by the satellite, and the use of these data in tropical analysis. Chapter 12 discusses such direct contributions of the satellite data to forecasting as are currently known. The operational potential of infrared data, when they become available to forecasters, is summarized and illustrated in Chapter 13.

Information provided in the appendices includes schedules and circuits used for disseminating meteorological satellite and ancillary data, and a reprint of an Air Weather Service study regarding the use of satellite data for analysis over areas of sparse conventional data.

To assist those who wish to look deeper into some matters than the space here permits, applicable specific references are listed in the rear of this report, and are keyed to the text by superscript numerals. Selected references with regard to general knowledge of the field of satellite meteorology are listed in Appendices E and F. *

* Extensive bibliographies on Satellite Meteorology have been published in the October 1960, March 1963, and February and March 1964 issues of Meteorological and Geoastrophysical Abstracts; and as: Kiss, E., 1963: Bibliography on Meteorological Satellites (1952-1962), U. S. Weather Bureau, available from Superintendent of Documents, U. S. Government Printing Office.

Progress towards improved interpretations of meteorological satellite data can be anticipated as continuing its rapid pace. Techniques developed subsequent to the preparation of this report will be available to Air Weather Service forecasters through the scientific literature. The Journal of Applied Meteorology, the Monthly Weather Review, and the Bulletin of the American Meteorological Society are among the publications that carry papers on these matters.

1.1 SOME GENERAL CONSIDERATIONS

1.1.1 State-of-the-Art Limitations

Satellite meteorology is still in only an early stage of its development, and this can be only a state-of-the-art report. While the information presented here has been drawn from all reasonably available sources, the studies and interpretations to date of meteorological satellite data are often less complete than would be desired. For many types of situations, only a very few case studies exist; rarely has it yet been possible to verify deductions with samples even approaching statistical significance.

On the other hand, the requirements of the Air Weather Service forecaster cannot wait until it is possible to complete studies satisfactory to the rigorous statistician. Accordingly, this report attempts to supply the forecaster with the best guidance currently available. In its preparation, considerations of the reasonableness of relationships so far observed between cloud patterns and conventional synoptic experience have most commonly constituted the justification for the concepts presented. Generalizations from selected case studies, as subjected to such considerations of reasonableness, are necessarily used far more frequently than is completely desirable. The authors will not be in the least surprised if many of the relationships discussed in subsequent chapters are modified to a greater or lesser extent during the next decade. But the material in this report should be beneficial when used cautiously; in each individual situation common sense and experience will indicate the weight to be placed on satellite data.

Even where no material operational application is now seen, it is important that the Air Weather Service forecaster learn to use satellite data and to integrate and compare it with conventional meteorological data and analyses against the day when he may be faced with making operational recommendations based on satellite data alone. In addition, in meeting the urgent requirements daily imposed on many AWS forecasters, the satellite observations can materially aid in analyzing areas otherwise nearly void of data.

1.1.2 Limitations to Practical Applications of Models

The analyst should also remember that many of the examples shown in this report, and in the meteorological literature on which it is largely based, define models of atmospheric conditions. The case studies provide excellent examples of what nature can do. But the only realistic use of atmospheric models occurs when they are treated as examples of conditions that occur in nature; not as rigid situations that will necessarily recur in all cases. Examples showing results of nature's mechanisms are certainly useful, but a particular example will seldom exist again in just that form. When dealing with a particular weather situation, the forecaster or forecast user (such as a pilot) should not assume a model (but rarely found) structure from which deviations are to be predicted on the basis of current observations. The more logical approach is to examine the factors which contribute significantly to the cloud and precipitation features in each section of the storm. Once the data relevant to each factor have been examined, the most probable conditions within the particular storm can be determined.[61]

GENERAL CONSIDERATIONS

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CHAPTER 2

GENERAL CONSIDERATIONS AND LIMITATIONS

The inherent nature of satellites and the orbits to which they are constrained place stringent limitations on the types, amounts, and scheduling of the data they provide.

2.1 ORBITAL FACTORS AND THEIR EFFECT ON COVERAGE

All satellite orbits are elliptical, with the center of the earth at one of the foci. For operational meteorological satellites, the orbit is made as circular as the guidance accuracy of the launch vehicle permits. In most TIROS, the departure from orbit circularity has been less than ± 25 nautical miles; in only one case, where a guidance system malfunction occurred, did the departure exceed ± 38 n. miles. Nimbus orbits are expected to be circular within ± 40 n. miles.* Accordingly, the forecaster can almost always consider the orbit as circular and the altitude of any given satellite as constant.

It should be noted that the plane of the orbit must pass through the center of the earth, and that the instantaneous intersection of the orbit plane with the surface of the earth must be a Great Circle. Small Circle orbits, such as a constant latitude (other than equatorial) orbit would require, are just not possible. Because of the rotation of the earth under the orbit, the subpoint path of the satellite intersects the instantaneous orbit plane at a small angle (of the order of 2^{o}), with the subpoint path directed to the west of the orbit plane.

Orbit altitude determines the speed of the satellite and so the period, the time for completion of one orbit. Since the earth rotates within the orbit, the period determines the westward displacement (relative to the earth) of each pass from the immediately preceding one. Typical values of these factors for present and foreseeable meteorological satellites are tabulated in Table 2-1.

* The Nimbus I orbit was much less circular than expected (263 to 580 miles) due to a second stage malfunction.

Table 2-1

Orbit Periods and Westward Displacements

Satellite Type	Orbit Altitude (n. miles)	Orbit Period (minutes)	Westward Displacement Per Pass (degrees longitude)
TIROS	350	97	24.2
	400	99	24.8
	450	101	25.2
Nimbus	500	103	25.8
	600	108	27.0
	750	113	28.2
Possible subsequent design	1500	145	36.2

A consequence of these westward displacements is that, for practical purposes, a single satellite can obtain data from any given area in low latitudes only twice a day at intervals about twelve hours apart. For sensors which can operate only with daylight illumination, this frequency of observation is usually reduced to once a day. Since adjacent orbits intersect at higher latitudes, several consecutive views of a given area, at intervals of about an orbital period, may be possible in middle and high latitudes; these groups of consecutive viewing periods are again centered about twelve hours apart for near-polar orbits, and normally about 24 hours apart for inclined orbits like those of the first eight TIROS. Typical TIROS and Nimbus (quasi-polar) orbits are shown in Figure 2-1 and 2-2, respectively.

Areas of coverage by TIROS* are also controlled by the orbit inclination, which limits useful data to between about 65°N and S latitude for the usual 58° orbit, and, in the case of the TV cameras, by a slow precession (rotation) of the plane of the orbit relative to the sun.[129] As shown in Figure 2-3, the latitudes where the satellite passes over areas of adequate illumination vary in a cyclical fashion with a period of about 2-1/2 months. In actual practice, the idealized regions shown in Figure 2-3 may vary up to some 30° in latitude and 10 days in time as a result of

* When only the name TIROS is used, it will generally refer to the configuration used in TIROS I-VIII, with the camera looking parallel to the spin axis. The term "TIROS Wheel" will be used when referring to the proposed modification whereby the cameras point out the sides and the spin axis is perpendicular to the plane of the orbit.

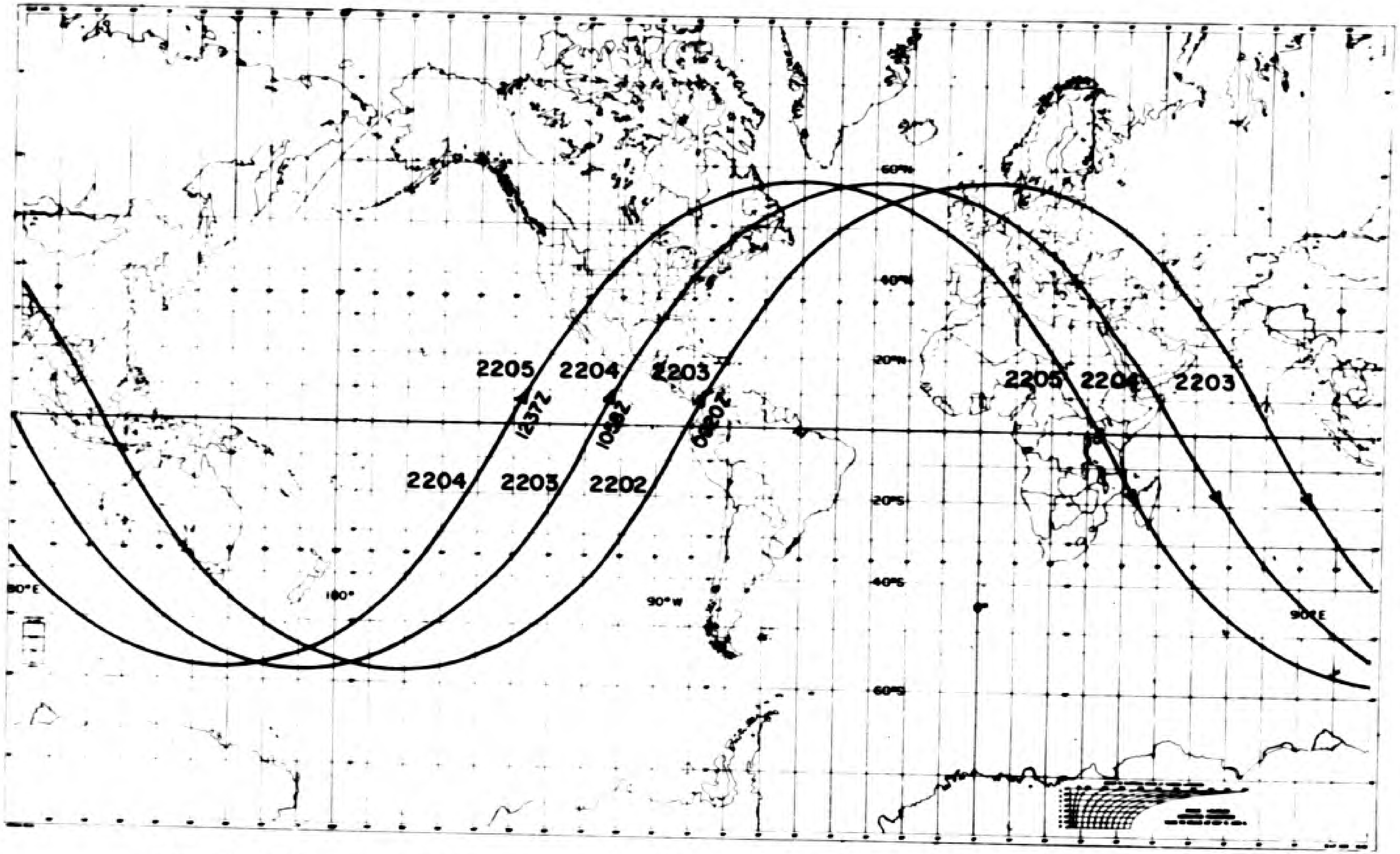

Fig. 2-1 Subpoint Tracks for Several Typical TIROS Orbits (TIROS VI Orbits 2202-2205).
Times at which Satellite Crossed the Equator Northbound on these Orbits are Shown

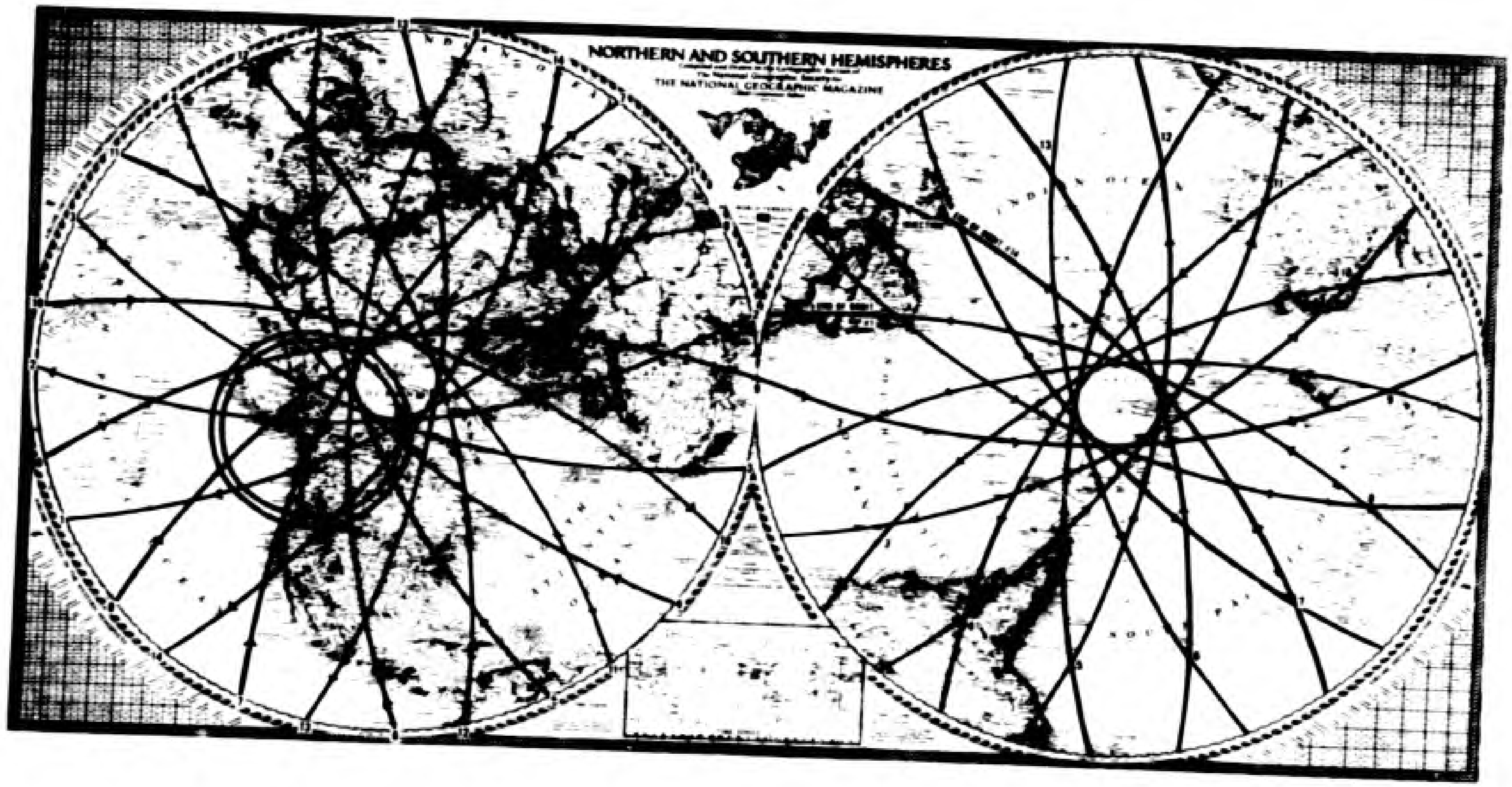

Fig. 2-2 Typical Nimbus (Quasi-polar) Orbits. The Double Circle Indicates the Approximate Limits of Range of the Fairbanks, Alaska, Command and Data Acquisition Station (From Reference 106)

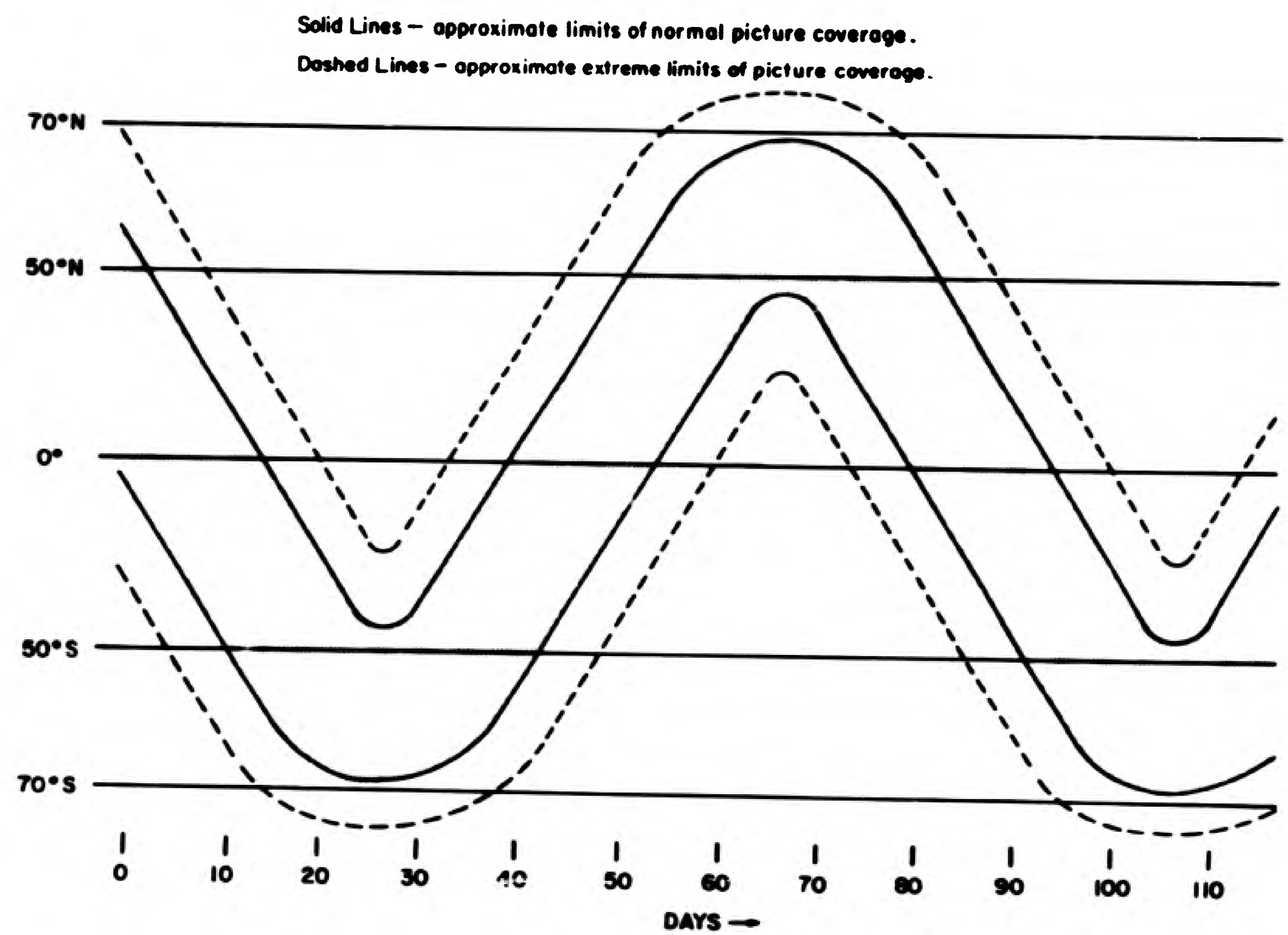

Fig. 2-3 Day-to-Day Change of Latitudinal Belt Observed by a Single TIROS

control of the satellite attitude (using the magnetic orientation coil) and decisions as to exactly which portion of the illuminated part of the orbit will be photographed. For both TIROS and Nimbus, locations of the command and data acquisition stations, and limitations to the data storage capabilities in the satellite may prevent obtaining data over certain longitudes. The precession of the TIROS orbit also causes the times of day at which data are taken to vary through the 2-1/2 month cycle.

For Nimbus and other satellites in near-polar orbits, including the TIROS Wheel, the precession of the orbit is chosen to just counteract the movement of the earth around the sun so that observations will be taken at the same local time each day. For Nimbus, the observations (except in high latitudes) are scheduled to be taken near local noon and midnight along the central meridian of the observed area.[3] However, observations at any other pair of local times twelve hours apart (i.e., 0300 and 1500; 0900 and 2100; etc.) are possible and launches into orbits suitable for such times of observation are possible.

Information on those areas where TIROS observations are anticipated is distributed by teletype and facsimile. The expected coverage for the next few days is provided each day; and three times a week an outlook for longer periods is provided. Daily Alert messages, providing information as to the next 24-48 hours, are distributed domestically by teletype and as a map over the National Facsimile Circuit. International teletype messages give daily global information for the next few days, and seven day outlooks on Monday, Wednesday, and Friday. Further details concerning these schedules and the code forms used are given in Appendix A.

An obvious consequence of these variations is that the satellite data will seldom be precisely concurrent with conventional synoptic observations. The time difference between the two types of data will vary with location and, in the case of TIROS, from week to week. Experience has shown that this is not a serious obstacle to effective application of the satellite data, since the majority of the observed features and patterns retain their identity over periods of time comparable to the time difference between synoptic and satellite observations.

2.2 COVERAGE, SCALE, AND RESOLUTION

2.2.1 Coverage and Scale

The area shown in a TIROS picture varies with the lens used, and with satellite attitude and altitude. For the wide angle lens (most frequently used) and a typical 400 nautical mile altitude, a single picture covers an area some 720 n. miles on a side when the camera is looking straight down (0° nadir angle). Figure 2-10 is an example of a low nadir angle picture of the area near the mouth of the St. Lawrence River. When the camera views the earth at an angle, the area seen varies. When a horizon is just barely seen (i.e., the satellite field of view includes mostly the earth and just a bit of sky) the distance from the foreground to the horizon may be as much as 1700 n. miles. Figure 2-9 shows such a case near Greenland. When the horizon crosses the center of the picture, as in Figure 2-11, it is about 1400 n. miles from the foreground and the visible distance along the horizon may exceed 2000 n. miles. Because of the angle of view, however, only the largest scale features can be seen near the horizon and the error in determining their geographical location may be substantial.

Where the medium angle lens is used in TIROS at a 400 n. mile altitude, the 0° nadir angle dimensions are about 460 n. miles on a side, with the other dimensions at varying angles of view approximately proportional.

The coverages provided by the Nimbus cameras at representative altitudes are given in Table 2-2. The "Along Track" dimension listed for the Side Cameras is a representative value measured mid-way in the field of view.

Table 2-2

Nimbus Camera Fields of View

Altitude (N. Mi.)	Camera	Coverage Along Track (N. Mi.)	Coverage Across Track (N. Mi.)
450	AVCS* Center	300	300
450	AVCS Side	350	570
450	APT*	960	960
500	AVCS Center	320	320
500	AVCS Side	420	660
500	APT	1,080	1,080
600	AVCS Center	400	400
600	AVCS Side	490	840
600	APT	1,320	1,320
750	AVCS Center	500	500
750	AVCS Side	630	1,260
750	APT	1,680	1,680

Because of the dimensions of the fields of view of the weather satellites, the scope of the cloud features seen is normally greater by an order of magnitude or more than that seen by an observer on the ground. Analysts with direct access to the pictures (including those from APT) must constantly guard against the tendency to relate geometric cloud shapes seen in the pictures to similar ones they have observed from the ground without regard for this tremendous difference in scale. Cloud forms and patterns visible from a single point on the ground are seldom discernible in a satellite photograph, since the entire area of the sky normally visible to a ground observer is only about one percent or less of that shown in a single satellite picture.

Nephanalysis strips prepared from TIROS pictures typically each cover areas of the order of 1000 n. miles wide and up to 5000 n. miles long. Useful data from the three camera Nimbus AVCS* array and from the Wheel TIROS will produce a strip about 1500 n. miles wide; while the pictures will extend from pole to pole

* AVCS = Advanced Vidicon Camera System
APT = Automatic Picture Transmission

(subject to illumination restrictions), the latitudinal length of individual neph-analyses to be prepared from them has not yet been established.

Since the various TIROS and Nimbus radiation sensors normally scan from horizon to horizon, the data when made available for operational use can be expected to be in swaths of the order of 1500 n. miles wide and of currently undetermined length. Other aspects of satellite radiation data will be discussed in Chapter 13.

When the satellite pictures view the earth at an angle, as in most TIROS pictures and the Nimbus AVCS side cameras, the effect of perspective on relative scales and locations within the picture must be considered. For TIROS, this effect is illustrated in Figure 2-4, where the grid lines shown have a relative spacing (except very near the horizon) equal to 3° of latitude (180 n. miles). Figure 2-5 shows the effect in the Nimbus side camera, using a 1° latitude-longitude grid network. For the forecaster having direct access to the pictures, guidance will usually be provided by a superimposed geographical grid incorporated before transmission to the station, or locally in the case of the APT pictures.[46,48] Examples of such grids can be seen in Figures 2-9 and 6-16.

The extreme effects of perspective near the horizon can produce significant errors in geographical locations. It is generally unwise to use data closer to a horizon than 10-15% of the overall width of a picture frame. Where unusual circumstances make it necessary to do so, great care must be used and the results derived should be appropriately qualified. The facsimile transmitted nephs normally do not include data from these areas.

Both operational experience and specific studies indicate that the errors in the geographical locations of features seen in the TIROS pictures (except near the horizon) should seldom be as great as 2° of latitude (120 n. miles),[1,8] and that they are more frequently of the order of 30 n. miles.*

2.2.2 Distortion

The appearance and relative locations of features seen in the satellite pictures are also influenced by distortion introduced by the camera lens. In the TIROS wide angle pictures, this distortion begins to become appreciable beyond a radius from the center of the picture about half-way from the center to a corner, and rapidly

* When adequate time and refined orbital and attitude data are available, as in the case of research projects, locations accurate to 10 n. miles or better are considered normal.

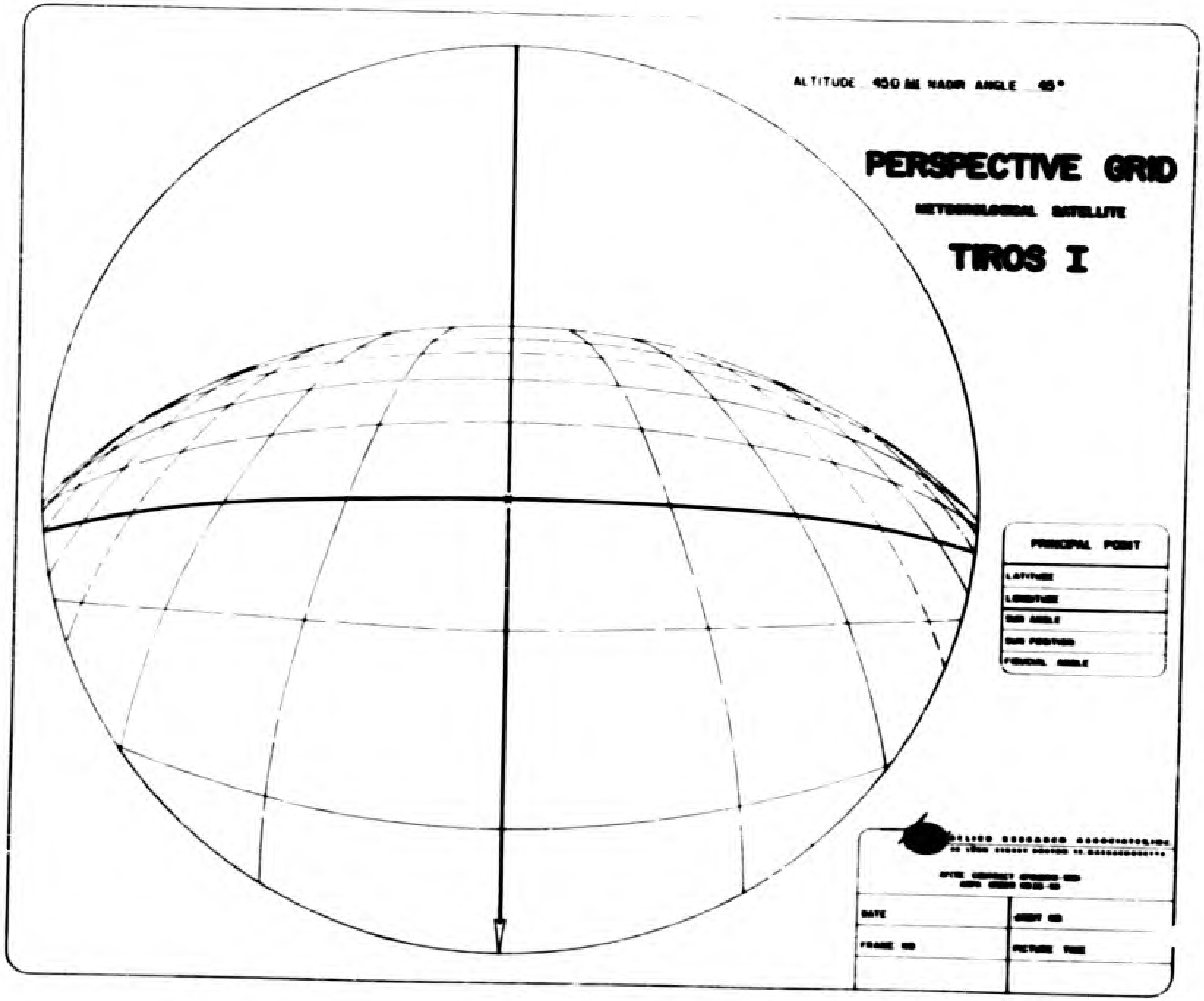

Fig. 2-4 TIROS Perspective Grid, Showing Scale Distortion

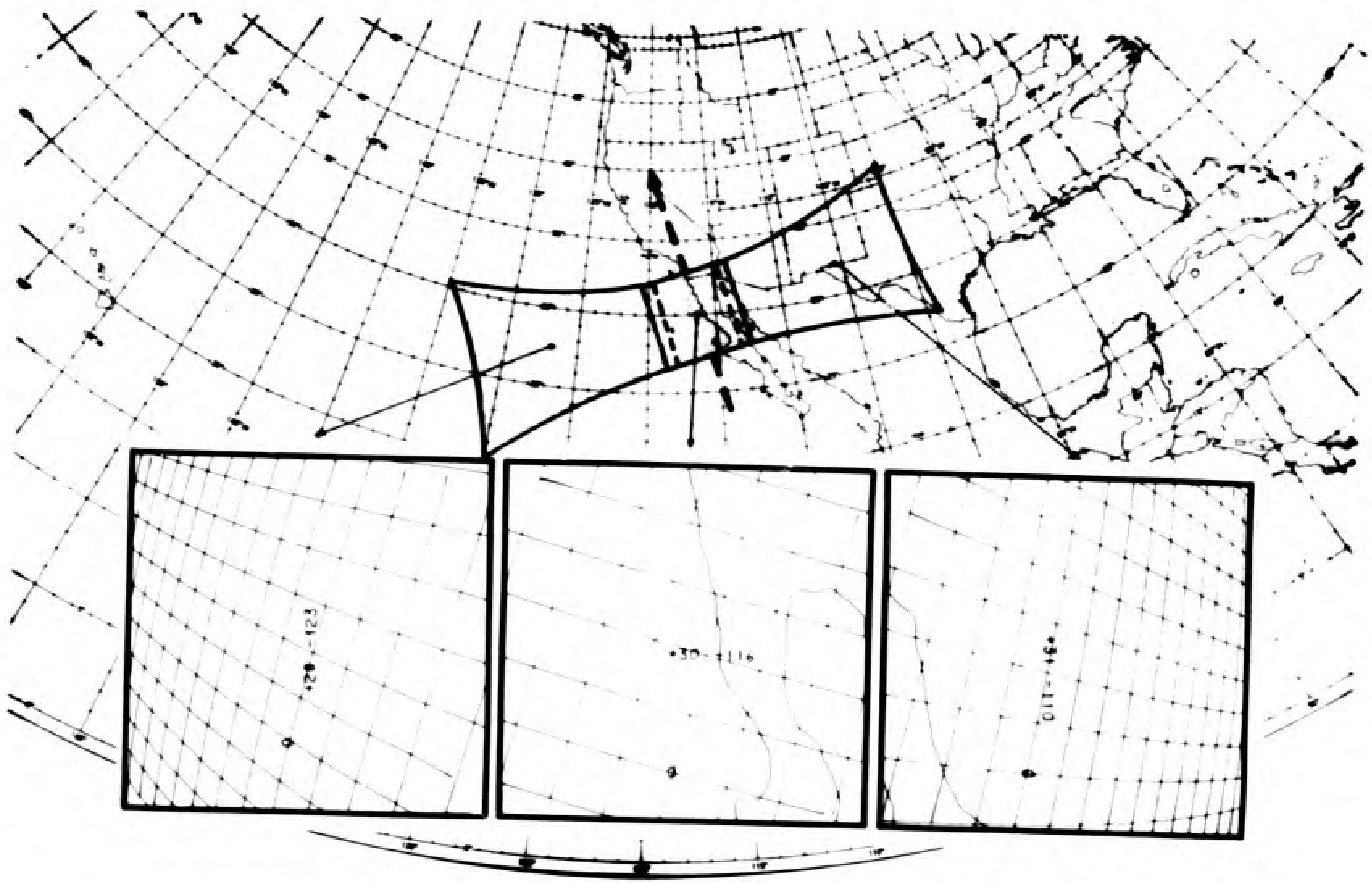

Fig. 2-5 Geographical Area Covered by One Nimbus AVCS Picture Triplet and the Corresponding Perspective Latitude-Longitude Grids

increases from there outward. The sense of the effect is to make features near the picture edges appear more compressed in the radial direction, and closer to the picture center, than they would without distortion. The visual effect is to accentuate the curvature of the earth, as shown by the horizon in such figures as 2-11. This so-called radial or symmetrical distortion has been taken into account in the geographical gridding procedures. For most operational purposes, the distortions to cloud features, in those cases where they are significant, can be detected from distances measured relative to, and in the same directions as, nearby grid line spacings.

Non-symmetrical distortions exist both in TIROS wide angle pictures and in those from other satellite cameras, due to optical imperfections, and to errors introduced by the various electronic components and the radio transmission link inherent in the overall satellite system. Usually these are too small to be of operational significance. Symmetrical distortions for other than the TIROS wide angle camera are operationally negligible.

2.2.3 Resolution and Contrast

The size of features that can be seen in the pictures is limited primarily by resolution, and to a lesser extent by contrast. Where contrast is extremely low, as in the case of clouds viewed against a uniform snow cover, even large features may not be visible.

2.2.3.1 Resolution

Resolution limitations arise from the dimensions of the scan used in the satellite TV systems.[29] Unless comparatively bright, isolated objects less than the width of a scan (or raster) line will not be visible.* Two features separated by less than 1.5 to 2 times the distance between the centers of scan lines will appear as a single object. On the average, the best resolution practically available from the satellite TV cameras is about 1-1/2 times the distance between the centers of the

* Since the TV integrates the total light across the scan spot, a very small but bright object can give the same response as a less bright object whose size is that of a scan spot.

scan lines as projected onto the image of the earth. Because of the effects of geometry and perspective, this distance increases and resolution decreases as the area viewed is located further from directly below the satellite. Approximate values of the best practically available resolutions for various satellite cameras and portions of the areas viewed are given in Table 2-3.

Table 2-3

Approximate Best Practically Available Resolutions

Satellite	Camera	Relative Location	Approx. Resolution (n. miles)
TIROS	Wide Angle	Directly Below Satellite	2
		Straight Down View, Near Picture Edge	4
		Straight Down View, Near Picture Corner	7
		1/10 frame width from horizon	10
	Medium Angle	Directly Below Satellite	1-1/2
		Straight Down View, Near Picture Edge	2
		Straight Down View, Near Picture Corner	3
		1/10 frame width from horizon	8
Nimbus	Center	Directly Below Satellite	2/3
		Near Picture Edge	3/4
	Side	Nearer Edge of Picture	3/4
		Further Edge of Picture	3
	APT	Directly Below Satellite	2
		Near Picture Edge	4
		Near Picture Corner	7

Even when satellite pictures are directly available to Air Weather Service forecasters, further effective degradations in the resolutions shown in Table 2-3 are probable as a consequence of the ground communications system or the APT receiving and recording equipment.

When clouds are arranged in narrow parallel lines, additional complications may arise from the relation of the scan lines to the locations and spacings of the cloud lines and individual clouds, and from the angle between the cloud line orientations and the scan pattern. In some cases cloud lines narrower than the scan line width may be clearly visible, while in others, lines wider than the scan line may be essentially impossible to distinguish. Narrow cloud lines are usually most clearly visible when they cross the rasters at an angle of about 45°,[17] as illustrated by Figure 2-6.

The consequences of resolution limitations may be demonstrated by considering cases of cumulus and cumulonimbus clouds, which have a wide range of sizes and spacings comparable to resolutions ranging from far finer than those provided by any operational meteorological satellites through all those in the right column of Table 2-3. Accordingly, different fields of cumulus suffer varying degrees of degradation when seen in the pictures, depending upon the size of the cloud elements in the particular field and upon the resolution available. For instance, in the case of rather widely scattered large cumulus, say 5 miles or more apart and about 1 mile each in diameter (somewhat like those in Figure 2-7, left portion within oval), and with a TIROS angle of view such that the resolution is about 2 miles, all of the clouds will be shown, but degradation will tend to make individual clouds appear larger but less bright than they really are. If the sizes of the clouds and the spaces between them are about the same or slightly smaller than the resolution, the clouds will appear larger but fewer in number than they really are (Fig. 2-7 , right portion within oval), owing partly to the fact that two or more clouds may appear as one. If the sizes of the clouds and their spacing are considerably smaller than the resolution, as with a field of small fair-weather cumulus, the area will appear more or less thinly overcast (Fig. 2-8), the brightness depending largely upon the ratio of total area covered by individual clouds to total area of intervening clear spaces. In such cases, especially with small and only scattered cumulus, the picture may show merely a grey tone, only slightly lighter than the underlying land surface, and at times indistinguishable from the appearance of haze or cirrus.

Another very significant consequence is that it usually is not possible to distinguish rows of fair-weather cumulus only a single cloud in width, as can be noted in Figure 4-2 when the satellite picture is compared to aircraft frame 373N. The rows that can be seen will be either groups of lesser rows several clouds wide, or result from a wind shear across the row which can lead to parallel cloud bands

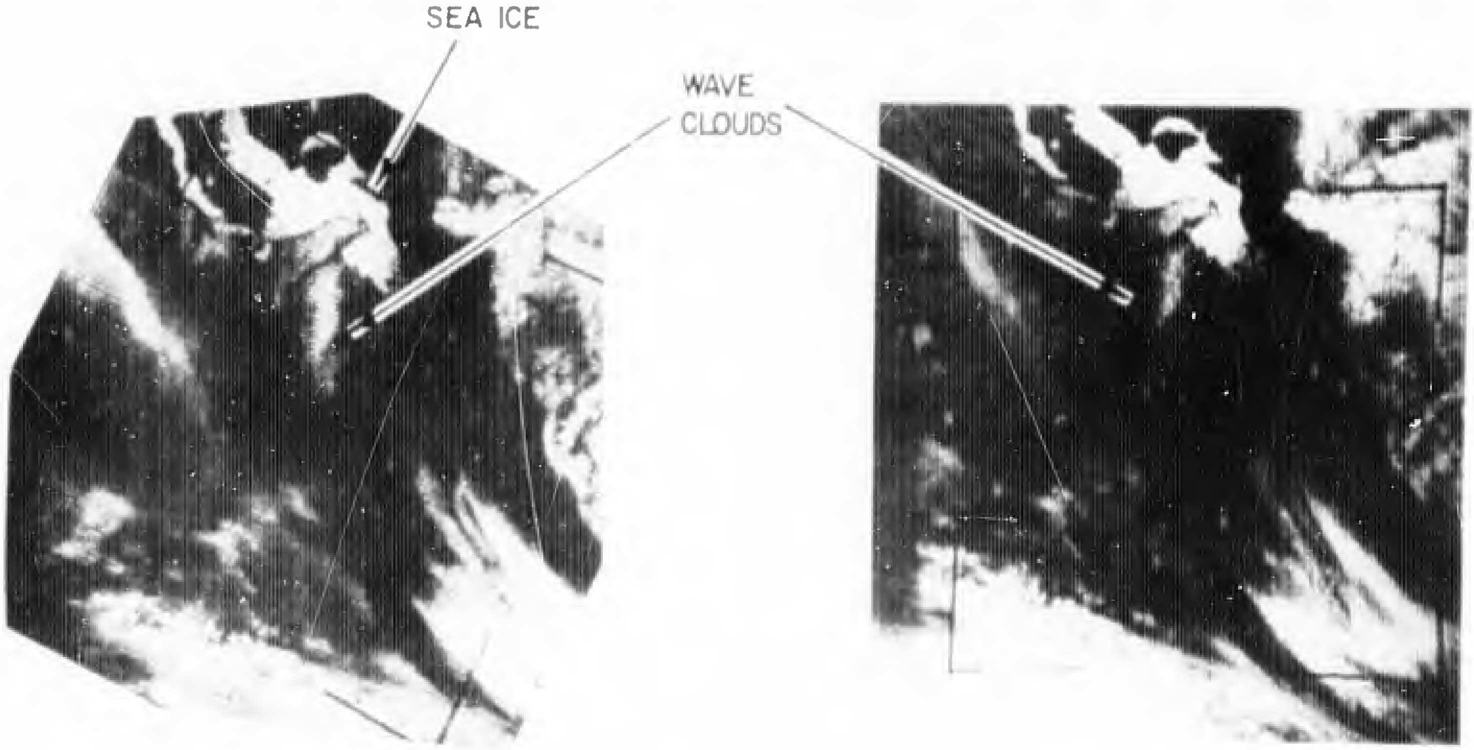

Fig. 2-6a Cloud Lines about 45° to Raster Lines. (Lines Easily Visible)

Fig. 2-6b Cloud Lines 90° to Raster Lines (Lines Obscured by TV Scan)

Fig. 2-6 Optimum Resolution of Small Scale Cloud Lines

Fig. 2-7 Widely Scattered Large Cumulus

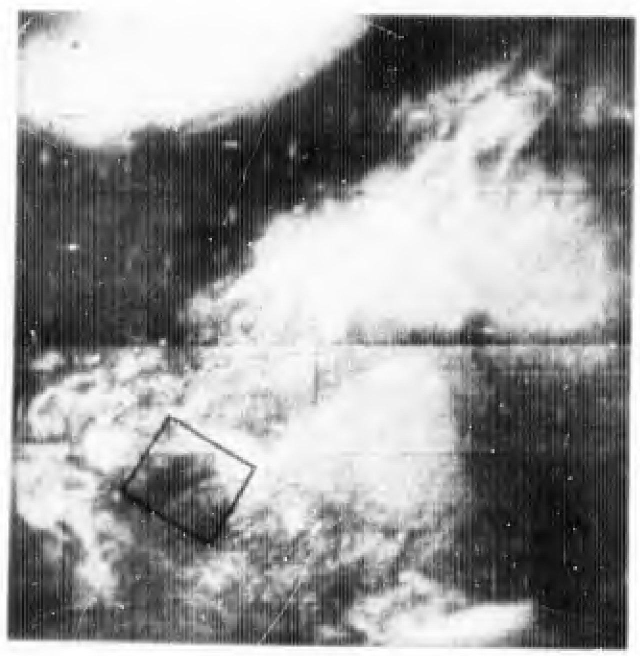

Fig. 2-8 Field of Small Fair-Weather Cumulus (Outlined area of picture)

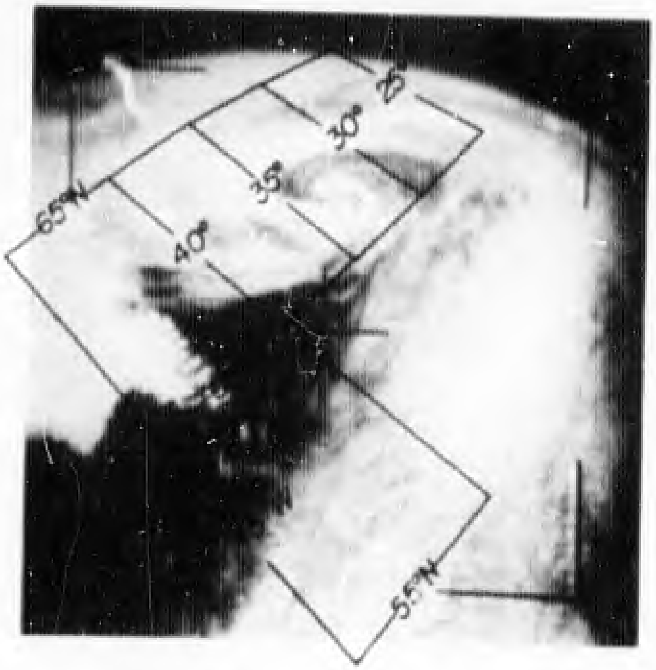

Fig. 2-9 Clouds above a Uniform Snow Cover

Fig. 2-10 Snow Fields and Ice Covered Lake

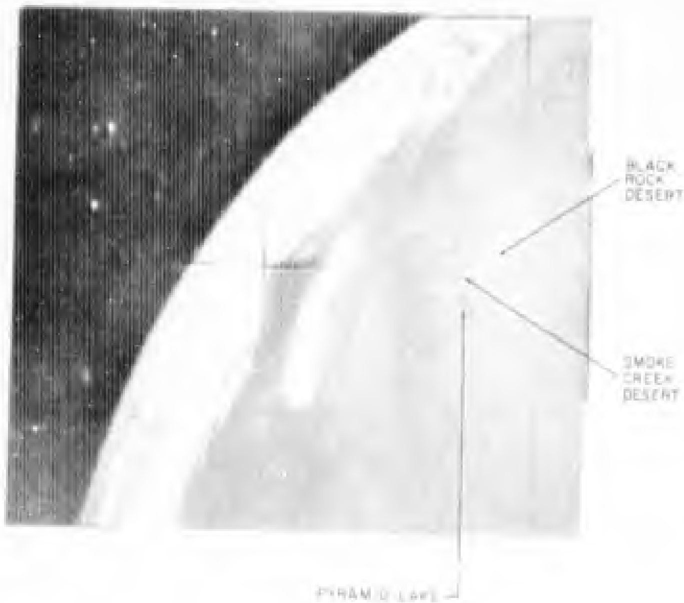

Fig. 2-11 Highly Reflective Deserts

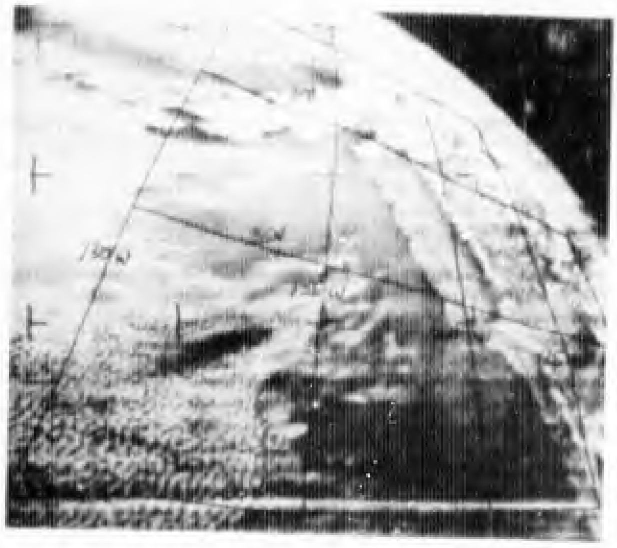

Fig. 2-12 Sample APT Picture, with Added Geographical Grid

more or less perpendicular to the individual cumulus rows and broad enough to be seen in the pictures.[8,68] Accordingly, the derivation of winds from cloud bands involves a number of uncertainties, as will be discussed in greater detail later (see Section 8.1.2.1 and Appendix C).

2.2.3.2 Contrast

Contrast also limits the features and details visible in the satellite pictures. Contrast can best be thought of as the degree of difference in brightness between two adjacent objects, or between an object and the background against which it is viewed. Obvious problem situations here include clouds above a uniform snow cover (Fig. 2-9, over the Greenland ice cap; Figure 2-10, left side) and higher clouds above a uniform undercast (see Fig. 4-15, left side, where cirrus overlies lower clouds). Thin clouds, especially cirrus, are often difficult or impossible to distinguish against the surface; more so over land than ocean because land surfaces are usually somewhat lighter than the black of water surfaces (see Fig. 4-3). Since fields of small scattered clouds below the limit of resolution (such as those in Fig. 2-8) produce an averaged response in the camera system equivalent to a thin overcast, they also may be difficult or impossible to see against the surface.

Where individual features only slightly larger than the effective resolution have low contrasts, they may be difficult to detect.

Degradations in contrast are inevitable in satellite pictures transmitted by facsimile, resulting from the necessary chain of photographic processing, scanning, electronic communication, and reproduction. Based on samples available from the TIROS VIII experiment, the APT pictures may also suffer from significantly reduced contrast due to the recording process. Figure 2-12 illustrates a TIROS VIII APT picture with relatively good contrast.*

2.2.4 Brightness

Brightness variations provide the primary basis for the initial gross recognition of features in satellite pictures. To a first approximation, areas can be categorized according to the following values of brightness:

* The Nimbus I APT pictures have shown excellent contrast and resolution.

Blackest	Outer space, above the horizon (Fig. 2-9, upper left).
Black	Oceans (Fig. 2-9), unfrozen lakes (Fig. 4-3) and rivers.
Dark Grey	Most land areas, especially those with forests or vegetation (Fig. 4-3, over Michigan).
Light Grey	Thin clouds (Fig. 2-9, just east of Greenland); scattered small clouds (Fig. 2-8); bright sand or desert areas (Fig. 2-11); old snow or ice.
White	Clouds of average thickness (Fig. 4-4); fresh snow (Fig. 2-9 over southern Greenland).
Very White	Thick clouds, especially large cumulonimbus masses (Figs. 4-9, 4-10).

Other examples of these brightness categories can be found in the many illustrations in subsequent chapters, and in various discussions of them.

The apparent brightness of cloud features as seen in the satellite pictures varies not only with the types of clouds and cloud systems viewed, where it can be a source of interpretative information, but with other factors that significantly increase the interpretation problem. These other factors include time of day (or angle of solar illumination),* angle of view, equipment settings, photographic processing, and direction of view relative to the sun.[29] Because of reflective effects, clouds are apt to appear unduly bright when viewed with the satellite looking to the sunward side of the vertical, and in or near the vertical plane that includes the sun and the satellite.** This is especially true in the vicinity of the point where geometric reflectance of the sun's image would be expected from a horizontal mirror surface, as in the central parts of Figure 10-14A. While this last effect is often obvious when a series of adjacent frames can be examined, such series are usually not available to the Air Weather Service forecaster. Accordingly, care must be used in making interpretations based solely on brightness, especially when the observed brightness gradients are smooth and symmetrical about a line or point.

* Which may cause the brightness to vary by as much as a factor of four.

** During periods when pictures are taken, the sun will be behind the plane of the lens of the camera.

2.2.5 Terrain Features

In addition to the role of the terrain as a background and the contrast problems it may thereby create, terrain features whose size is about that of common clouds or cloud features may lead to interpretation problems.[14,22] Bright surface areas, such as snowfields (Fig. 2-10), ice-covered lakes (Figs. 2-10, 9-3), and highly reflective sand, salt-flats, and deserts (Fig. 2-11), may be mistaken for clouds. The darker appearance of a lake or large river may, when viewed through a uniformly thick cloud cover, give the appearance of reduced cloud thickness or some other type of patterning. Fog or stratus in river valleys may be mistaken for cumulus[8] (see Fig. 10-1).

In some cases, the interpretation may be rather obvious, as in the case of extensive snow cover over mountainous areas where the feathery edges produced by altitude variations and river valleys are frequently apparent (see Chapter 9, Fig. 9-4). Maps of significant terrain features over the United States, as they appear from TIROS in late winter and early spring, have been prepared.[22]

The forecaster with direct access to photofacsimile or APT satellite pictures should undertake to develop a familiarity with significant terrain features in his area of concern (just as he would for the radar ground pattern), including how their appearance in the pictures varies with season and snow cover. Good pictures showing such features should be filed for future reference and for training newly assigned personnel.

In addition to preventing erroneous interpretations of cloud features, a knowledge of terrain can be extremely helpful in interpreting terrain-related cloudiness, such as upslope stratus, mountain cumulus, and lee waves (see Chapter 8).

2.3 AVAILABLE DATA FORMATS

Meteorological satellite cloud picture data will be presented to Air Weather Service forecasters in one or more of the following formats:

- Facsimile nephanalyses
- Teletype coded nephanalyses (NEPAN)
- Photo-facsimile-transmitted selected pictures
- APT pictures

2.3.1 Photofacsimile Pictures

Selected pictures of cloud systems judged to be especially significant are transmitted by photofacsimile from the National Weather Satellite Center, but are available to only a very few Air Weather Service units. They may be provided as individual frames or mosaics of several frames. Latitude-longitude grid lines are included on the pictures and provide location, scale, and perspective information.[48] Degradation in resolution and contrast is to be anticipated as a result of the transmission process. Nevertheless, they are the highest quality pictures available, on an operational basis, except at the satellite data read-out stations and the National Meteorological Center.

Dissemination circuit information, current at the time of writing, is given in Appendix A.

2.3.2 APT Pictures

APT pictures (Fig. 2-12) are available only to those with the necessary receiving equipment. For satellites in a near polar orbit, data should be available as:

About 3 pictures from passes essentially overhead

One to two pictures from passes within about 1500 miles

More passes and pictures can be intercepted by stations at high latitudes.

Procedures for the acquisition, location, rectification, and geographical gridding of APT pictures are published elsewhere.[46]

As discussed above, present APT receivers provide data of relatively poor contrast, as can be noted in Figure 2-12. Effective resolution to date has been significantly less than anticipated from the characteristics of the equipment listed in Table 2-3. Future satellites may provide significantly better pictures.*

2.3.3 Facsimile Nephanalyses

Most Air Weather Service facilities have access to the facsimile nephanalyses (such as those in Fig. 10-2), which are currently the primary method for wide dissemination of meteorological satellite data. Circuits on which they are currently transmitted are listed in Appendix A.

* This has since been confirmed by the Nimbus I APT pictures.

The nephanalyses are prepared at the satellite data acquisition stations and re-transmitted, after being checked for general accuracy and compatibility with other available data and analyses, from the National Meteorological Center. They are intended to provide the maximum of information available from the cloud pictures that is feasible within the limitations of present weather communication facilities and the overall requirements placed on them. Since the beginning of 1964 they have been prepared not only to depict the geometric characteristics visible, but to emphasize the large scale cloud patterns which suggest synoptic features. Boundaries are chosen to emphasize cloud organization rather than arbitrarily selected changes in the amount of cloud cover. Because many of the key features observed in the satellite pictures are at a smaller scale or of a greater degree of subtlety than can be depicted geometrically or purely by symbols, interpretation thru the liberal use of remarks is encouraged. The currently used notations are shown in Figure 2-13 and their use is illustrated in subsequent portions of this report, especially Chapter 10.

Although the nephs are necessarily condensed depictions and interpretations of the pictures, experience has shown that they provide a large amount of information having direct practical operational application. The forecaster who disregards the nephs and the information in them is placing artificial limits on the weather information he can provide, just as he would by ignoring other significant data inputs. Methods of interpreting and applying these data will form the bulk of the discussions of this report.

The forecaster must be aware of the limitations of the nephs. The nephs can be no better than the satellite pictures on which they are based, and are affected by resolution, contrast, and position accuracy considerations discussed earlier. They are prepared with only conventional facsimile weather analyses available to make such limited comparisons as very tight schedules permit. Although the nephs are checked against the conventional analyses before re-transmission from the NMC, integration with conventional data and analyses, and the interpretation of the totality of the meteorological information available, must (at least for the present) be performed chiefly at the receiving weather stations and centrals. (The information in the nephs does influence subsequent conventional facsimile charts as transmitted from the NMC).

The nephs are principally valid as gross synoptic depictions. While considerable mesoscale information is included and is vital to interpretation of the synoptic scale conditions, the mesoscale detail must be used with care when

CUMULIFORM CLOUD — STRATIFORM CLOUD

CIRRIFORM CLOUD — APPARENT CUCG OR CB

BOUNDARY OF MAJOR CLOUD SYSTEMS - FRONTS, VORTICES, OR OTHER SYSTEM DOMINATING THE SCENE VIEWED BY THE SATELLITE

DEFINITE BOUNDARY OF MORE OR LESS UNORGANIZED CLOUD MASSES

INDEFINITE BOUNDARIES OF MORE OR LESS UNORGANIZED CLOUD MASSES

STRIATIONS

STRIATIONS, TENUOUS

CLOUD LINES

CLOUD LINES, TENUOUS - CLOUD FORM DENOTED BY , , ,

DIRECTION OF SHEAR OF CIRRUS - FROM CB ANVIL OR OTHER SOURCE

WAVE CLOUDS (MOUNTAIN OR TRANSVERSE)

ESTIMATED LOCATION OF JET STREAM - SHAFT MAY BE BROKEN TO AVOID OBSCURING SYMBOLS INSIDE NEPH BOUNDARY

VORTEX — HEAVY + — THIN —

CLOUD	SIZE (n. mi.)	OPEN SPACES
1	0-30	6
2	30-60	7
3	60-90	8
4	90-120	9

CLOUD AMOUNT

OPEN (O) = <20% coverage
MOSTLY OPEN (MOP) = 20-50% coverage
MOSTLY COVERED (MCO) = 50-80% coverage
COVERED (C) = >80% coverage

NOTE: STIPPLING WILL BE USED TO EMPHASIZE THE AREAS CONSIDERED BY THE ANALYST TO BE OF GREATEST SYNOPTIC SIGNIFICANCE.

Fig. 2-13 Coding Conventions Used in Preparing Facsimile Nephanalyses from Satellite Data interpreted at its own scale, especially as regards precise location. Key synoptic features, such as the apparent centers of cloud vortices and major cloud bands, are entered on the nephs with location accuracies normally of the order of $\pm 1^{\circ}$ of latitude. Pressure of time may force the analysts to be somewhat less careful in the entry of finer details. And while location errors of $\pm 1^{\circ}$ are seldom critical to synoptic scale interpretation and application, that much error can be very significant at the mesoscale. For example, it would be unwise to combine a convective line position from a neph and a subsequent radar observed position to extrapolate to a predicted time of arrival of the line at a nearby airbase. Nevertheless, the data in the nephs can in many cases be of considerable aid in mesoscale interpretations, as will be discussed in Chapter 8.

Where the neph provides meteorological interpretation in addition to objective geometric depiction, misinterpretations do at times occur. Cirrus bands have been depicted as lines of cumulus; fog in valleys (such as that in Fig. 10-1) has been labeled as scattered cumulus; parallel cumulonimbus anvils have been mistaken for cloud streets.[8] When the information in the neph conflicts with other available data, a misinterpretation should be considered as one (but only one) possibility. The possibility that the satellite data are correct and the other information is in error should also be given consideration.

The few cases of errors in interpretation that do occur are more than outweighed by the additional information provided in the majority of situations, especially since gross errors are usually prevented by the check before retransmission at the NMC.

2.3.4 Coded (Teletype) Nephanalyses (NEPAN)

Stations lacking facsimile (unless equipped with APT) can receive the satellite data only in the form of the coded teletype transmissions (NEPAN). The code used and the circuits on which transmissions are made are given in Appendix A.

The teletype nephanalysis code provides, for each one-degree square (in latitude and longitude), an indication of the cloud amount, type, and description felt to be most indicative of that one-degree square as a whole. Cloud amounts are specified in such terms as open, mostly open, covered, mostly covered, and, combinations thereof. Cloud types are cumuliform, stratiform, cirriform, cumulonimbus, or combinations thereof. Cloud descriptions include such categories as thin or dense, convective cellular, bands, and indications of vortex or frontal characteristics.

Obviously, the teletype nephs can provide only synoptic scale cloud patterns. In areas of plentiful sources of other data and analyses, they seldom add greatly to information inherent in the other data. In sparse data areas, the additional information provided by such nephs can be extremely significant and may at times exceed that from all other available sources.

CHAPTER 3

THE NEED FOR COORDINATION AND INTEGRATION WITH OTHER OBSERVATIONS AND ANALYSES

The meteorological data obtained from satellites in the form of TV pictures (and hopefully, in the near future, from the infrared radiometers) provide a valuable tool for the forecaster.

3.1 THE VALUE OF SATELLITE DATA

The operational value of the synoptic data derived from the satellite pictures (or, later, radiometric data) may vary significantly from one area to another, from one synoptic situation to another, and from one operational problem to another. While the satellite data can contribute significantly over all areas, in data-sparse areas their contribution is especially valuable. For example, many features such as cloud vortices, synoptic size crescent-shaped cloud patterns related to upper level troughs, cloud bands, etc., (which are discussed in detail in later chapters of this report) will allow a better synoptic analysis to be drawn by utilizing whatever conventional data are available and supplementing the conventional data with that from the satellite pictures, or vice versa. In data-sparse areas such as the central Pacific Ocean, synoptic features, such as closed circulation centers in the mid-troposphere, often must be located on the basis of very few conventional data points which may often be hundreds of miles remote from each other. In some cases a pressure center may even be more than a thousand miles from the nearest data point.[8] Obviously, the location and central pressure of such a system cannot be determined accurately using conventional data, nor can the size of the area within the last closed isoline be determined to more than a rough first approximation. Yet the variations in size and intensity of these centers, their precise locations, and their day-to-day movements are among the fundamental parameters used by the forecaster. Thus any additional data that can be provided by the satellite pictures and nephanalyses which can aid the analyst in determining location, size, shape, and movement of circulation centers or indeed, whether or not an upper level trough has a closed circulation, are very valuable and must be incorporated into present analysis and forecasting techniques. Even over areas with relatively greater data density, such smaller scale features as squall lines, edges of cloud masses, etc., may add significantly to the analysis.

3.2 THE VARYING ROLES OF THE SATELLITE DATA

The optimum role of the satellite data will usually vary with the availability of other types of data. Where conventional observations are relatively plentiful, the satellite data will usually serve primarily to modify or aid in the interpretation of an analysis made initially from the conventional data. In data sparse regions, the satellite data should become at least coequal with other observations and may even become the primary basis of the analysis, but with due care to try to achieve an analysis compatible with all sources and types of data. Accordingly, several possibilities exist for the use of the satellite pictures or nephanalyses in the preparation of a synoptic analysis. An analysis may at times be prepared almost exclusively from the nephanalysis (or a composite of several nephanalyses) while, in other cases, one may use the cloud pictures as a simple check on a conventional analysis.

For example, in the absence of conventional data, large scale streamline patterns may often be inferred from the streaky appearance of middle and high clouds associated with cloud vortices, bands, etc. These streamline patterns, coupled with climatology, allow reasonable estimates to be made of 500 mb large scale synoptic patterns such as major ridges and troughs[76] (see Appendix B).

A second illustration of the use of satellite data during an initial analysis over data-sparse areas develops from the accepted practice in such cases of relying heavily on continuity. Often, in such cases, data from a single station may appear to be in error. Perhaps the wind direction or speed does not fit the pattern expected from continuity. As a result, such a data point is often disregarded where continuity would argue against inserting a developing pressure minimum or other new synoptic feature. A check of available nephanalyses or pictures might reveal a significant cloud mass and suggest an early stage of vortex development. Thus the single data point, coupled with the satellite cloud data, may lead to a revised analysis which in all probability would be far superior to the analysis based solely on continuity.

Even in cases where a relatively dense weather network exists, it is often possible to obtain information from the satellite pictures (or nephs) which will supplement the conventional analysis and allow better interpretations and/or forecasts to be made. These additional data may include both features difficult to identify in the conventional data (such as lines of cumulus activity or squall lines), or mesoscale features whose size is below the spacing of conventional data networks, such as clouds related to mountain ranges or topographic effects. Examples of such types of satellite observed features which may be added to conventional data to obtain a better mesoscale analysis and hence a better forecast will be discussed in some detail in Chapter 8.

It has been repeatedly shown that the availability of satellite pictures allows many improvements in the analysis of conventional meteorological charts for tropical regions[21]. As a synoptic system progresses through a region of comparatively dense data, the characteristics of the system can be determined and compared to the known cloud configuration as shown by conventional and satellite data. When the system moves into data sparse regions, the orientation and organization of the satellite observed clouds may lead to logical conclusions as to the changes in strength and location of the system.

The time-honored principles of continuity and vertical consistency for analysis in data-sparse regions remain as valuable as ever, but the satellite photos augment these techniques by alerting the analyst to unsuspected new developments. Knowledge of cloud cover in a data-sparse region is a great aid in drawing isopleths of meteorological parameters which better portray actual conditions. For example, if continuity is poor and observing points widely scattered, analysts tend to interpolate linearly between reported values of meteorological parameters. Satellite data may help immensely to correct this tendency by furnishing an accurate horizontal distribution of cloud cover.

Satellite observations have proven extremely valuable during the seasons of peak tropical storm development. The types of recognizable patterns and a discussion of them are presented in Chapter 11.

Where data other than the satellite observations are sparse, the forecaster should also make the fullest possible use of all other information at his disposal, including such considerations as climatology, synoptic climatology, physical relationships, and applicable current prognostic charts. The use of these aids in association with the satellite data will also be considered in more detail in Chapter 10.

CHAPTER 4

CLOUD TYPES - RECOGNITION, INTERPRETATION, AND USE

Although the principal concern of the Air Weather Service forecaster will normally be with the larger scale features and patterns seen in the satellite data, some cloud type identification is implicit in the interpretation of the larger features. Forecasters with access to facsimile or APT pictures will be handicapped in cloud type recognition and interpretation by the inevitable degradation in resolution and contrast of the pictures available to them. Even with high quality TIROS transparencies and the lesser time pressures of laboratory research studies, many aspects of cloud type recognition are difficult and, at times, completely unambiguous identifications are just not possible. Accordingly, only a summary of cloud characteristics as photographed from satellites is included here. Forecasters with access to reasonable quality satellite pictures may wish to consult References 14, 15, 16, 28, and/or 29 for more detailed discussions of cloud identification guidance.

Detailed and precise cloud type recognition is not essential to significant practical use of the satellite pictures. Studies made with pictures or data of poor resolution have shown that, in general, the cloud cover alone enabled recognition of major frontal bands, post-frontal areas, large scale vortices, and well developed ridges or high cells.[43] The contrast between the relatively unbroken and extensive cloud fields associated with fronts or pressure centers, and the broken and mottled appearance of the post-frontal areas, is usually distinct, even though small-scale cloud features are obscured. The jet stream location can often be inferred from the over-all cloud cover pattern.[49] Such results emphasize the great value of the facsimile nephs or even, if nothing better is available, the teletype nephs.

The analyst must keep in mind the differences between the ground-based view of clouds (as he is used to seeing and analyzing them) and the satellite view. Included are such factors as the relatively limited field of view of the ground observer, the method of reporting what the ground observer sees, and the difference in perspective.

Some of these differences are schematically illustrated in Figure 4-1. Figure 4-1a shows a sharp-edged cloud mass, which both the satellite and ground observer may view as such. But because of the method of reporting sky cover, ground based reports show a gradual transition across the boundary from clear,

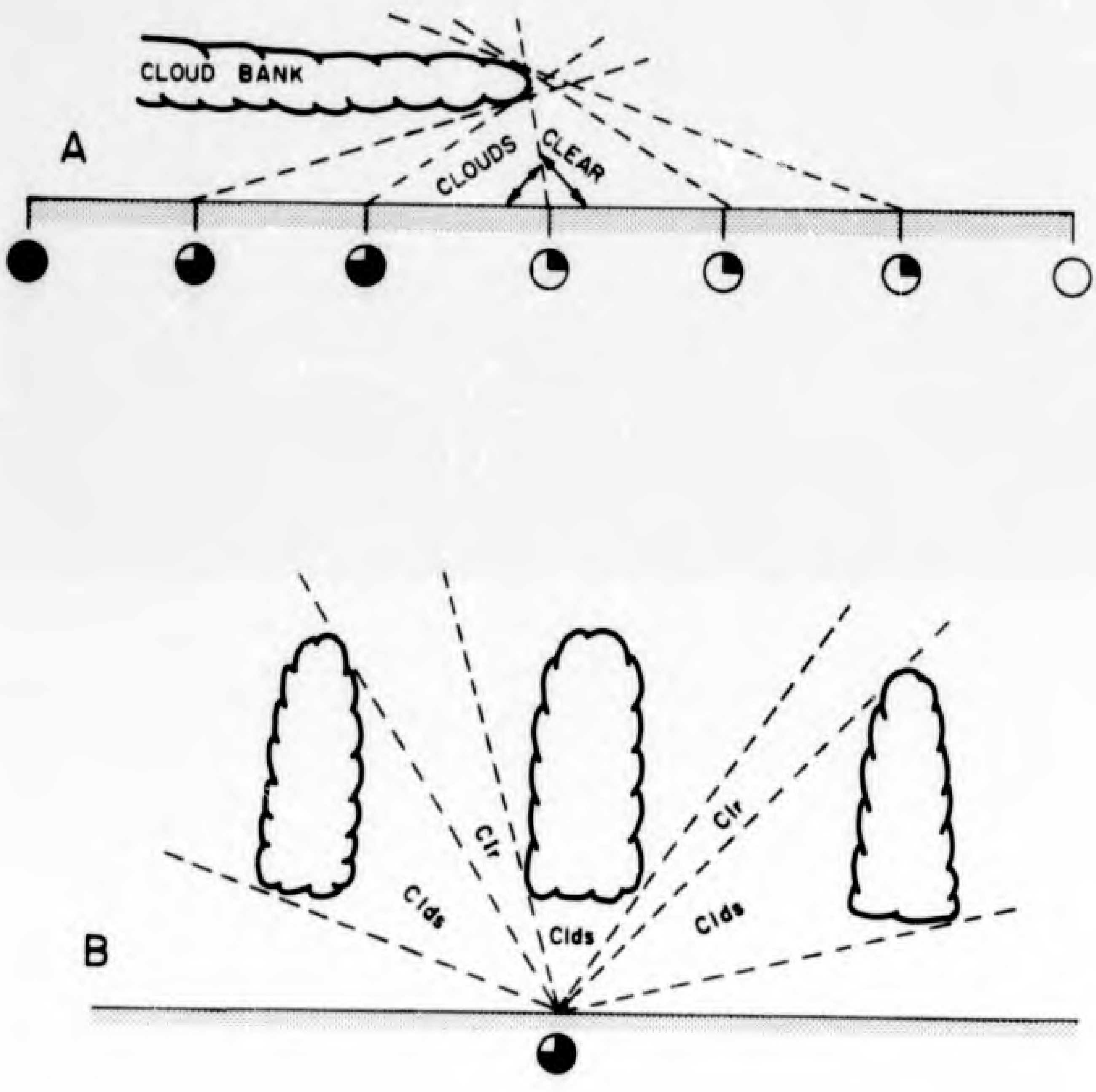

Fig. 4-1 Schematic Illustration of Difference in Perspective between Satellite and Ground Observations of Clouds. (From Reference 50)

through scattered and broken, to overcast. Figure 4-1b is intended to show isolated cloud masses, such as towering cumuli, which are scattered in amount and are so viewed by the satellite overhead. However, because of vertical development, the observer on the ground is able to see less of the sky through the clouds, and usually overestimates the amount of cloudiness.[50]

Because the entire sky as seen from a point on the ground covers such a small portion of the area of a single satellite picture, it is not feasible to illustrate an actual concurrent ground and satellite view of cloud cover. Figure 4-2 may, however, be helpful in relating satellite and more normal views of cloud patterns, since most Air Weather Service personnel have had some experience in observing clouds from aircraft. Figure 4-2 shows some oblique aircraft photographs taken, looking northward, essentially concurrently with the satellite picture which included the same areas.[17] The southern and side boundaries of the areas included in the aircraft pictures have been indicated on the satellite picture.

Matters pertinent to some of the other limitations to satellite cloud observations were discussed in Section 2.2.

The following discussions have been extracted in modified form principally from References 14 and 29.

4.1 GENERAL CONSIDERATIONS

Most individual clouds in the pictures cannot be seen because of their small scale (as Fig. 4-2 clearly illustrates), and therefore they cannot be identified as they are when seen from the ground. In their place, groups or clusters of individual clouds are seen.

Although the resolution of the cameras will not permit visual detection of many small-scale features that identify cloud types to the ground observer, the nature of the clouds often may be deduced from grosser features. The following is a general guide to interpretation; specific cloud types are mentioned later:

1. Raster line width should be considered in estimating minimum sizes of visible elements (see Section 2.2.3.1).

2. Knowledge of the azimuth of the sun and the position of the sunpath is desirable, because of their respective influences on shadows and the overall brightness distribution within the picture. Brightness itself is so complex that only qualitative inferences may be made, and measurements are meaningful only in the comparative sense.

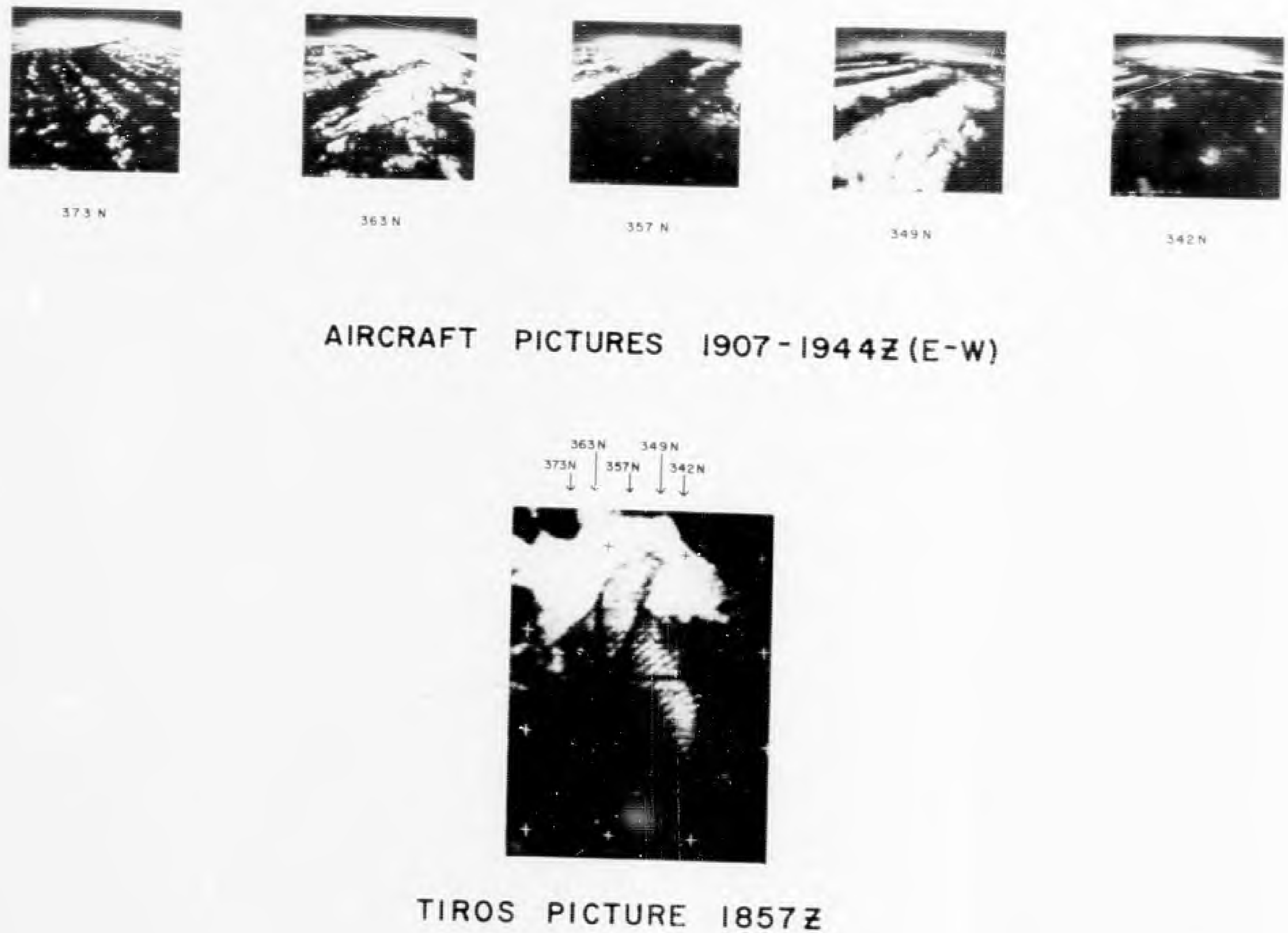

Fig. 4-2 Comparison between Aircraft and Satellite Views of Clouds (From Reference 17)

In view of the many factors affecting brightness,* one might expect to see a great variety of brightness changes that are impossible to interpret in terms of cloud characteristics. However numerous comparisons have shown that the situation is not so bad;** in fact, local increases of brightness are generally associated with increases in total cloud thickness, especially in cyclonic cloud systems, and it appears that a fair estimate can be made as to whether precipitation may be occurring or not, depending upon the brightness.***

Reports show that patterns of white on grey, such as those in the upper and lower parts of Figure 4-15, often correspond to widely-spaced undulations in the cloud tops; the whiter bands correspond to the area of thicker cloud. At other times this pattern may represent build-ups of low cloud below a translucent overcast.

Stratus or stratocumulus layers, which generally have high albedo when seen from aircraft altitudes, often appear grey. This may be because the layer is not homogeneous over the areas resolved by the camera and translucent portions are integrated with opaque portions to yield a cloud that appears mottled or grey. For the same reason, the estimation of precipitating areas from the cloud brightness within a cyclone apparently is related to the fact that precipitating and adjacent areas are covered with solid clouds while, outside these areas, bright clouds may be common but they are interspersed with thin clouds or thin areas. This produces an integrated picture of gradually increasing brightness from the edges of the cloud system to the precipitating area.

Comparisons also show that water clouds always appear brighter than ice clouds of the same thickness under similar conditions of illumination. Most cirrus and cirrostratus without underlying cloud are translucent; and, when reported as "scattered" by ground observers, they are invisible to the satellite except under conditions of strong illumination and dark background. These clouds alone probably never exceed the brightness level of grey.

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* Some of which were mentioned in Section 2.2.4. For a fuller discussion, see Reference 14, pp. 6-7, and/or Reference 29, pp. 17-20.

** Perhaps because the eye appears to compensate for the average brightness of the picture or region of the picture being examined.

*** It must be realized that not all bright clouds precipitate and, even for those that do, only a small portion of the bright area is likely to be precipitating at any one time. There is frequently, however, a fair correlation between the general shape and size of a bright cloud area as seen from a satellite and the total area over which precipitation occurs at one time or another within a period of a few hours. 77

3. Knowledge of or reconciliation with the synoptic situation and climatology is helpful and sometimes necessary for correct interpretation. The land-water effects on cumulus distributions, for instance, are inescapably obvious in some pictures and may readily lead to the interpretation of cumulus clouds even though individual cloud elements are not resolved (see also Section 8. 1. 2).

4. Visible cumuliform structure often consists of clusters of smaller, less visible clouds. The apparent elements, whether clusters or individual clouds, tend to appear slightly larger and fuzzier than they really are, owing to degradation.

5. From the picture appearance there is the tendency toward overestimation of thick cloud cover near the horizon, due to perspective; and underestimation of thin cloud cover at vertical view, due to transparency.

4. 2 CATEGORIZATION BY APPEARANCE

Approaching the cloud identification problem first from what is seen in the pictures, the following categories of the appearance of clouds can be established:

4. 2. 1 No Clouds Visible - Apparently Clear Skies (Fig. 4-3). The situation may be exactly as it appears. But there is almost an equal probability, depending in part on the quality of whatever pictures are available to the analyst, that such areas may be partially or completely filled with thin cirrus or cirrostratus in amounts ranging from scattered to very thin overcast, or by small, scattered, fair-weather cumulus. With good quality pictures, cirrus more extensive than thin, scattered can generally be detected with careful examination.

4. 2. 2 Cumuliform* Appearing - Straight or Slightly Curved Bands (Figs. 4-4, -5, -6). Clouds of this pattern are cumulus, stratocumulus, and cirrus. The pattern develops most frequently at low and high levels within the troposphere; relatively small differences in the appearance of the pattern may be associated with completely different processes taking place in the atmosphere. The bands may be approximately parallel, perpendicular, or (less frequently) at other angles to the wind. There are theoretical reasons for believing that cumulus cloud bands actually

* The term "Lumpy" has recently been suggested[18] as preferable to Cumuliform in order to differentiate between the scale of the cauliflower appearance as seen from the ground and that visible in the satellite pictures. It seems likely to be widely adopted in future publications.

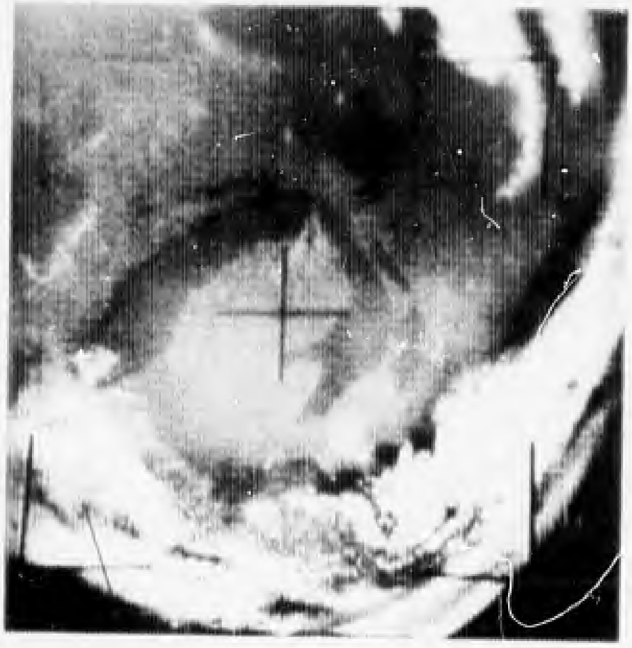

Fig. 4-3 No Clouds Visible; Apparently Clear Skies over Area in the Center of the Picture. Thin Cirrus was Reported over Upper Michigan.

Fig. 4-4 Cumuliform Appearing Straight or Slightly Curved Bands. Cirrus on Warm Side of Jet

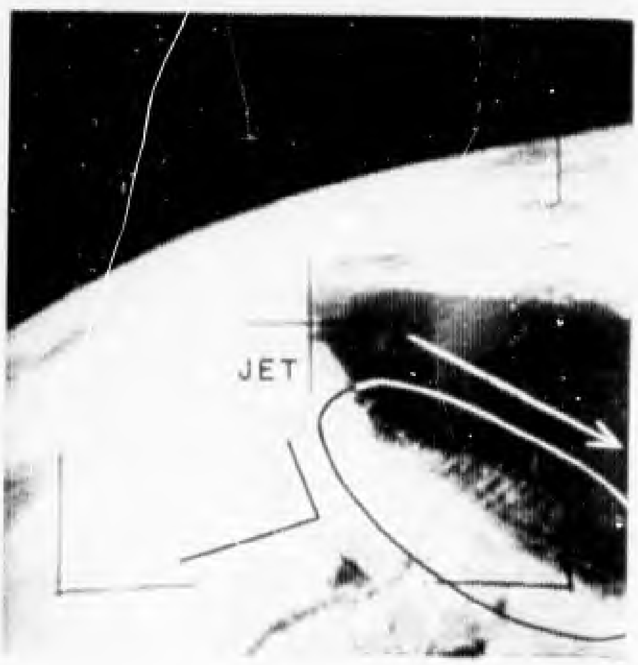

Fig. 4-5 Billow Clouds - Cirrus

Fig. 4-6 Wave Clouds - Stratocumulus (Square shaped bright cloud near upper left is a cumulonimbus mass which produced locally severe weather)

parallel the vertical wind shear rather than the wind; but generally the shear through the convective layer is nearly parallel to the wind direction. Where the uncertainty in wind direction is $\pm 180^{\circ}$, the correct direction can sometimes be deduced from cumulus or stratocumulus patterns if land-water discontinuities are present and an indication of whether the clouds are forming over the land or water is available (see also Section 8. 1. 2).

Cirrus bands found on the warm side of the jet stream usually exhibit cumuliform as well as noncumuliform characteristics (Fig. 4-4).* These bands are oriented parallel to the shear and in these cases are also parallel to the wind. These bands should not be confused with long cirrus blowoffs emanating from cumulonimbus clouds. The latter can be identified by the bright round-shaped cumulonimbus at the head of the band (see Fig. 4-9); this condition is most often seen in the tropics where the necessary shear between low and high level winds is more often found in conditions suitable to the formation of cumulonimbus.

Other, less pronounced cirrus bands will lie parallel to the shear and, for relatively light winds, may be oriented up to 90° from the wind direction. Because of such ambiguities possible with currently available interpretation techniques, all available conventional data should be considered when analyzing satellite pictures for wind patterns.

Billow and wave clouds are generally perpendicular to the wind. Billow (Fig. 4-5) and wave (Fig. 4-6) clouds tend to be shorter than cloud streets or other formations paralleling the wind, but positive distinctions between these clouds and convective types, from the satellite picture alone, are at best difficult. Wave clouds are most frequently found to the lee of hills or mountains (see Section 8. 2. 3); they have a large range of wave lengths, and billows may at times be seen within the waves.

4. 2. 3 <u>Cumuliform Appearing - Not Banded - Solid Cells</u> (Figs. 4-7 through 4-10). These include either random or evenly-spaced cumulus, stratocumulus, altocumulus, or cumulonimbus clouds. Cumulus of fair weather, stratocumulus, and altocumulus must be present in broken amounts to be visible (Figs. 4-7 and 4-8).

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* This and many of the subsequent figures in this chapter were taken from Reference 15. Unless otherwise indicated, the area of interest is that encircled. The superimposed "L" provides the scale in the directions perpendicular and parallel to the horizon, with each segment of the "L" being about 110 nautical miles long.

Fig. 4-7 Cumuliform Appearing Solid Cells - Stratocumulus

Fig. 4-8 Cumuliform Appearing Solid Cells - Strato or Altocumulus

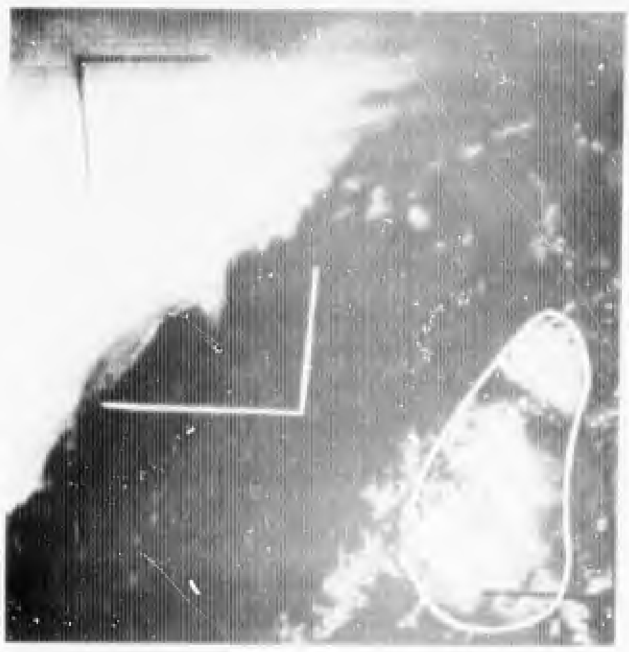

Fig. 4-9 Cumuliform Appearing Solid Cells - Cumulonimbus with Cirrus Anvils

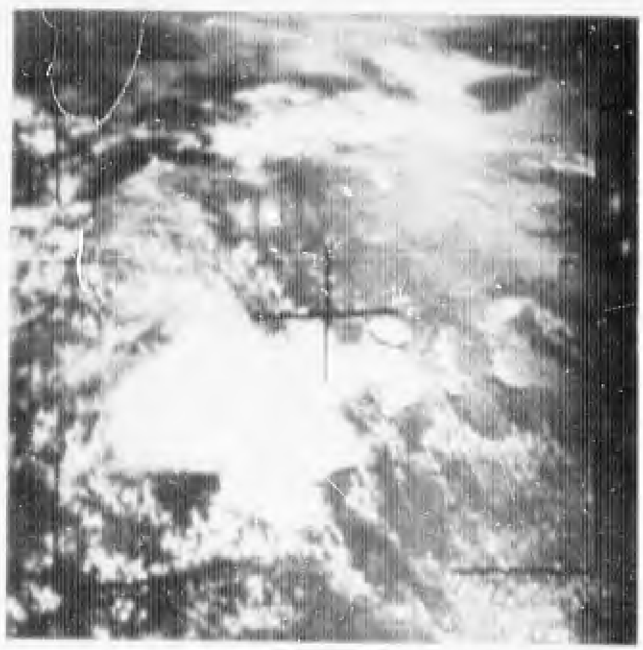

Fig. 4-10 Cumulonimbus with Debris Cloudiness

Fully developed cumulonimbus clouds are very white, and they are often characterized by one side that rapidly shades from very white through grey to no cloud. This corresponds to the thinning cumulonimbus anvil as it shears to one side (Fig. 4-9). As convective activity in this category increases, more thunderstorm debris cloudiness* may be seen between the brighter clouds and may eventually obscure the cumuliform structure (Fig. 4-10).

4.2.4 Cumuliform Appearing - Not Banded - Hollow Polygonal Cells or Crescents (Fig. 4-11). The hollow polygonal cells and crescents consist of patterns of cumulus and towering cumulus arranged in rings or crescents. The crescents are generally oriented in the same direction, with the surface wind blowing into the open sides of the crescents at angles up to 45°.

4.2.5 Cumuliform Appearing - Vermiculated** Banding (Fig. 4-12). This pattern is found especially over the oceans, in the trades and in the cold air flow behind major cyclones. The pattern represents cumulus and stratocumulus, often below an inversion. Winds in the convective layer tend to be fresh-to-strong, and to parallel the general orientation of the bands or to cross them at a slight angle toward lower pressure. As the shear weakens, the pattern tends towards crescents and, as the shear approaches zero, to polygonal cells. Weakening or rising of any inversion above the cloud tops may also lead to the transition to crescents and subsequently to polygonal cells.

4.2.6 Stratiform Appearing - Banded (Figs. 4-13 and 4-14). This category includes wave (Fig. 4-13), billow, and jet-stream (Fig. 4-14) clouds that do not show cumuliform characteristics. The cloud types may be stratocumulus, altocumulus, and cirrus.

4.2.7 Stratiform Appearing - Not Banded - Fibrous (Figs. 4-15 and 4-16). Such clouds are cirrus, altostratus or stratus. In the case of cirrus, in spite of the great difference in scale it often appears similar to cirrus as seen from the ground (Fig. 4-15; the cirrus is the band of grey cloud to the left of the center fiducial). Sometimes the cirrus is observed in the form of a single band adjacent to the jet

* Scud and smaller cumulus and stratocumulus formed between the major convective cells.

** Vermiculated means with a wormlike, or an irregular, twisted appearance.

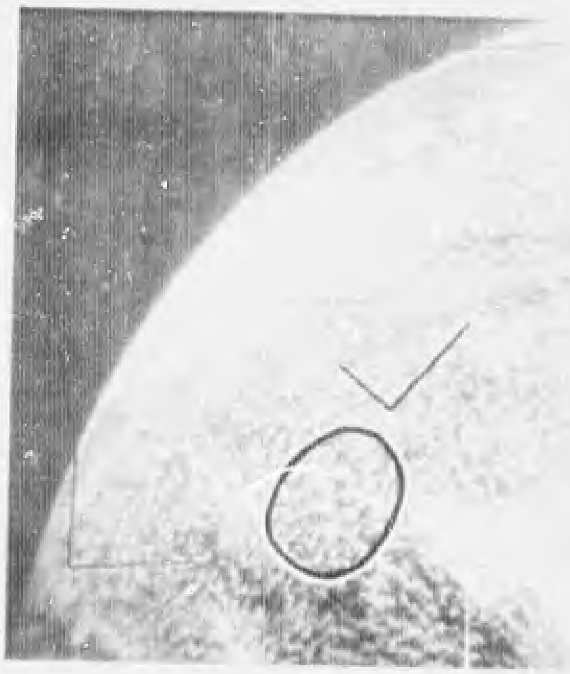

Fig. 4-11 Cumuliform Appearing Crescents - Cumulus humilis, Cumulus Congestus

Fig. 4-12 Cumuliform Appearing Vermiculated - Cumulus Congestus

Fig. 4-13 Stratiform Appearing Banded-Wave Clouds - Stratocumulus

Fig. 4-14 Stratiform Appearing Banded-Jet Stream Cirrus

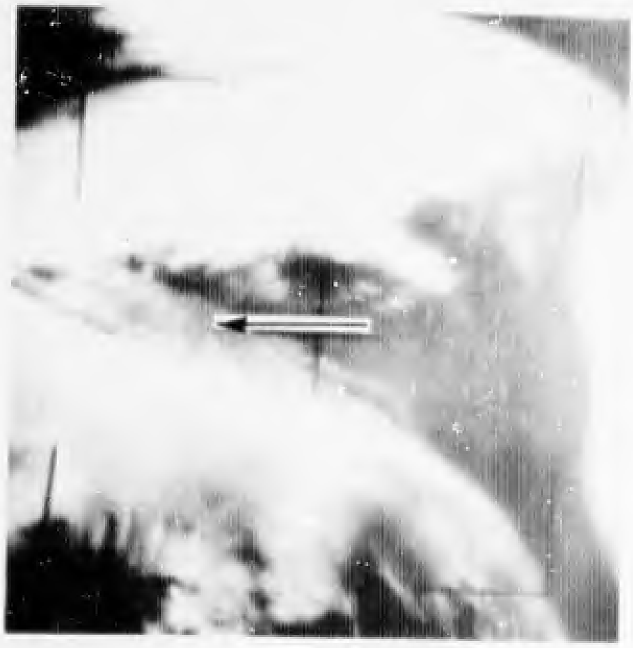

Fig. 4-15 Stratiform Appearing Fibrous-Cirrus

Fig. 4-16 Stratiform Appearing Fibrous-Stratus

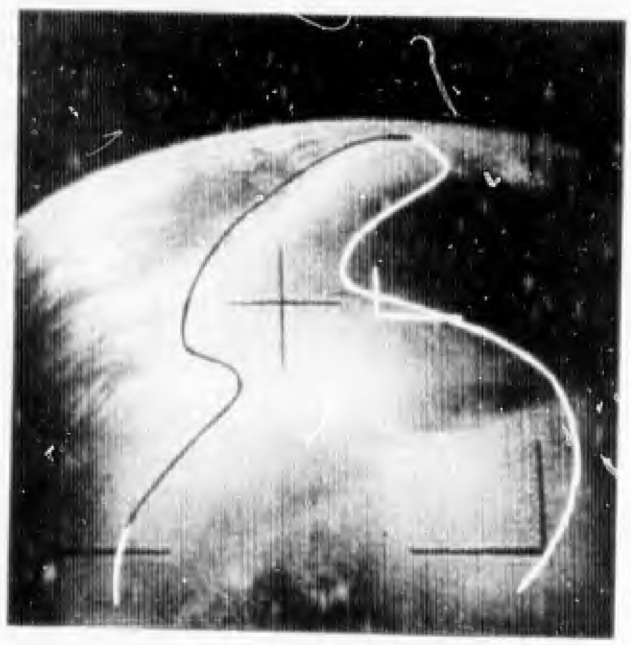

Fig. 4-17 Stratiform Appearing Neither Banded Nor Fibrous - Alto-stratus

Fig. 4-18 Stratiform Appearing Neither Banded Nor Fibrous - Dust stream and on the warm side. Fibrous character stratus is most often noted in the stable areas west of California and northern Mexico over the eastern Pacific (Fig. 4-16), off northwest Africa in the eastern Atlantic, and other climatologically similar regions.

The fibrous or streaky appearance is most probably produced by the side-by-side advection of clear air and cloud elements by a streaky wind field.* Whenever the horizontal displacement of cloud elements of a non-uniform deck is much greater than their vertical displacement, or if the uniform deck is advected by a streaky windfield, clouds will have a fibrous appearance along the wind direction. This will be revealed if there is adequate contrast in the pictures. It is a frequent phenomenon, and much interpretation of satellite pictures for synoptic analyses owes its success to it.[55] Specific examples, on the large or quasi-hemispheric scale, are illustrated in Appendix B.

4.2.8 Stratiform Appearing - Neither Banded Nor Fibrous (Figs. 4-17 through 4-21). This includes sheets of clouds, or dust. A field of a few small cumuliform clouds such as cumulus or stratocumulus has also been found with this appearance because the available resolution is inadequate to define them. Dark grey or grey clouds consist of broken-to-overcast cirrostratus, broken stratus, or moderately thin but overcast stratus (Fig. 4-17). Dust has a similar appearance (Fig. 4-18). Uniform white clouds indicate thick stratus or stratocumulus (Fig. 4-19), or an overcast of combined nimbostratus, altostratus, and altocumulus which may yield light precipitation (Fig. 4-20). Uniform very white clouds (Fig. 4-21) are indicative of a nimbostratus overcast, perhaps as several layers, with a good probability of yielding precipitation (see footnote on page 37).

4.3 CATEGORIZATION BY CLOUD TYPE

The above discussion has presented cloud identification from the viewpoint of what is seen in the pictures which is, of course, the actual starting point for any practical analysis. Many persons, however, find it easier to mentally catalog such

* By the term streaky, we mean a wind field where narrow bands of relatively lower and higher wind speeds are found side by side, with the streaks paralleling the direction of flow. Parallel bands of relatively greater and lesser humidity may also contribute to the streakiness observed in the pictures.

Fig. 4-19 Stratiform Appearing Neither Banded Nor Fibrous - Overcast Stratus

Fig. 4-20 Stratiform Appearing Neither Banded Nor Fibrous. Overcast Nimbostratus - Altostratus - Altocumulus. Light Precipitation.

Fig. 4-21 Stratiform Appearing Neither Banded Nor Fibrous - Nimbostratus Active. Rain and Thunderstorms

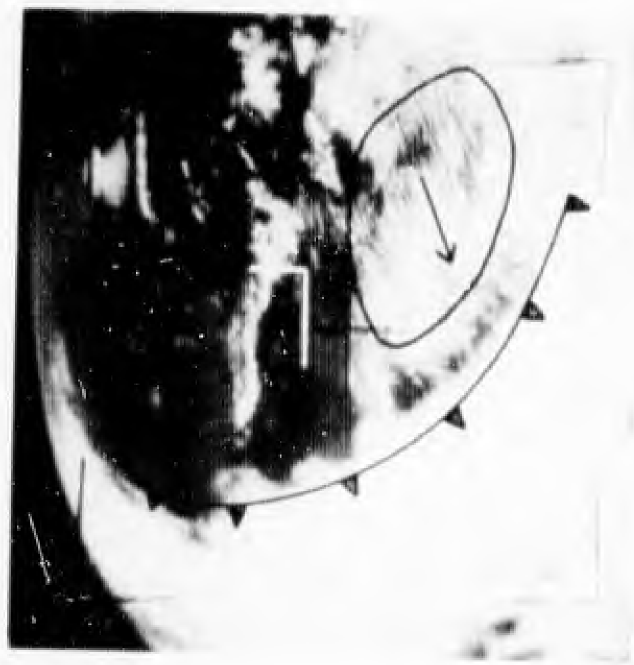

Fig. 4-22 Stratocumulus Cloud Streets.

information in terms of the more familiar cloud types with which they are already accustomed. Accordingly, similar information is summarized below from this point of view.

4.3.1 Cirrus or Cirrostratus. Thin cirrus or cirrostratus is often not visible (Fig. 4-3). Thick cirrus is visible, except against a background of lower cloud masses (Fig. 4-15; the cirrus is obviously visible in the break, to the left of the center fiducial, between the lower cloud masses. Careful inspection shows it also extends over the lower clouds at the bottom of the picture). It often reveals bands (Figs. 4-4 and 4-14), striations, or a fibrous appearance oriented approximately parallel to the wind at the cloud level, and similar in appearance to what often is seen from the ground (Fig. 4-15). The scale can be expected to be an order of magnitude or more larger. Identifying characteristics: fibrous appearance, relatively low brightness, relative insensitivity to geographic effects (i.e., cirrus will stretch across coast lines without change, Figures 4-25, 2-9, whereas cumulus - as discussed below - is usually more extensive over land than water, or vice versa, depending on the season). When cirrus emanates from thunderstorm cumulonimbus, or from the major convective cloud masses found in active tropical storms, the brightness will decrease in the direction away from the source (Fig. 4-9) and the winds at the cirrus level can be assumed to blow from the brighter or thicker portion of the cloud towards the darker or thinner portion[8] (see Section 11.5.3).

4.3.2 Small Fair-Weather Cumuli (Individual Clouds 1/2 Mile Or Less In Diameter). These ordinarily are completely unresolved and appear as a nebulous sheet of relatively low brightness (see that part of TIROS picture in Fig. 4-2 photographed in Aircraft Frame 373N). At times, the area may even appear clear. Cumuli are distinguishable from cirrus by their total lack of fibrous appearance and their sensitivity to land-water areas (Fig. 8-5). Areas of fair-weather cumuli may exhibit a slight granular texture when viewed at low nadir angles, believed to be caused by a non-random grouping of cloud elements which individually are too small to be resolved.

4.3.3 Cumulus and Stratocumulus Cloud Streets. The cumuliform structure of these is visible only in areas of the pictures with comparatively high resolution (i.e., near the center of low nadir angle pictures). The parallel-line structure is more easily seen (Fig. 4-22) but also disappears under unfavorable conditions. As discussed in Section 2.2.3.1, it is usually not possible to distinguish rows of fair-weather cumulus only a single cloud in width. The line structure disappears when closer to the horizon than 50% of the width of a frame. The overall aspect is then like that of randomly scattered small cumuli -- a uniform area of relatively low brightness.

4.3.4 Towering Cumuli (Individual Clouds 1/2 to 2 Miles in Diameter). At low nadir angles, and for broken cloud cover, the appearance definitely is cumuliform (Fig. 4-23). The distance between apparent elements usually is between 5 and 15 miles, and one sees largely the clusters rather than individual clouds. Larger nadir angles, more widely scattered clouds, and the coexistence of much cirrus or small cumuli decrease the cumuliform appearance and may eliminate it. The combination of scattered towering cumuli within a field of small cumuli, or with considerable cirrus, appears as a spotted or mottled sheet, the spacing of the spots averaging 5 to 10 miles. This is a relatively small-scale phenomenon, not easy to see.

4.3.5 Cumulonimbus and Thunderstorms. These are definitely of visible size, and if not too deeply imbedded in other clouds appear as bright blobs 5 to 20 miles in diameter, or in patches up to 50 or more miles across (Fig. 4-9). The larger sizes are clusters of cumulonimbus clouds, with apparent size enhanced by degradation and the anvil formation of dense cirrus (Fig. 4-10).

Pre-existing layers and the cloud debris attending thunderstorms may completely obscure the cumuliform structure. The existence of thunderstorms and/or clusters of towering cumuli near the cumulonimbus stage may be inferred from the splotchy appearance of the cloud masses and the relatively abrupt gradations in brightness (Fig. 4-10).

Prominent cloud patterns producing locally severe weather exhibit some common characteristics. They are distinguished from other cumulus cloud patterns by the medium scale size and the unbroken, uniform appearance (Fig. 4-10). They are usually either separated or completely isolated from other cloud cover, and in

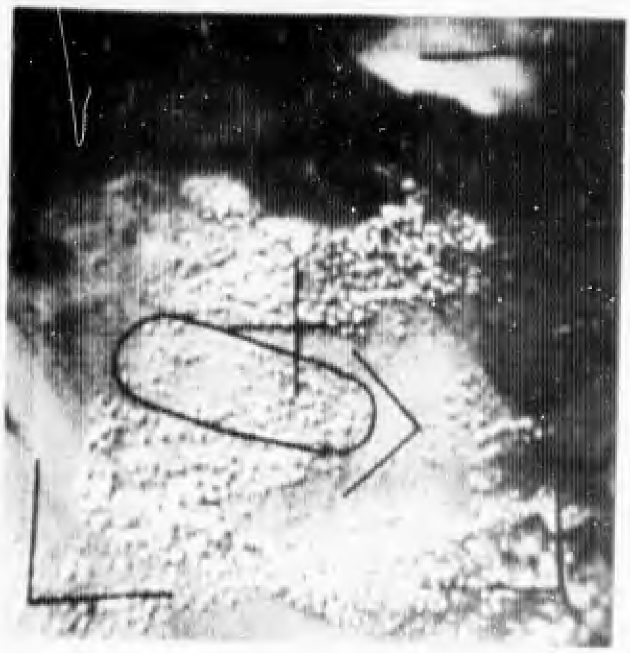

Fig. 4-23 Towering Cumuli

Fig. 4-24 Bright Overcast Strato-cumulus

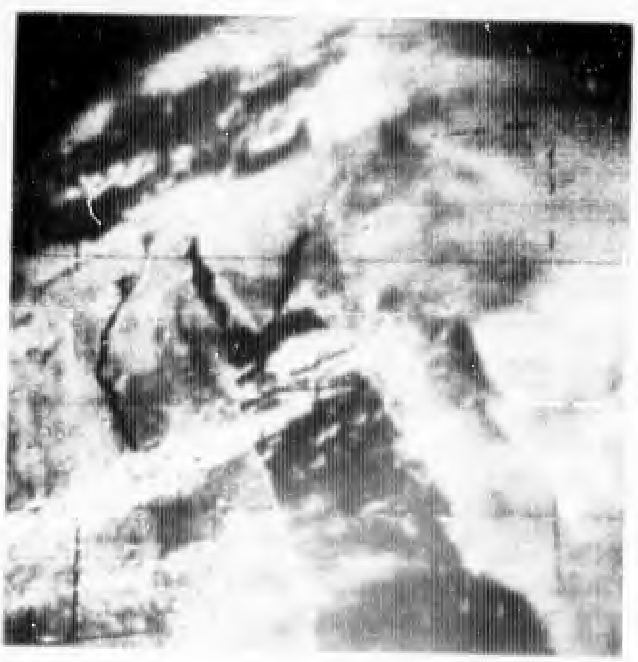

Fig. 4-25 Example of the Insensitivity to Geographic Effects of Cirrus

the large-size range of the mesoscale spectrum, measuring between 100-200 miles in length; the bright, "square" cloud in the upper left of Figure 4-6 is an example. Being usually of a similar transverse dimension, they appear as massive cloud blobs; this is one of their most distinctive characteristics. Although each pattern is a large unit with little internal detail, the sharply defined borders, the scalloped appearance along portions of the border, and the overall intense brightness are indications of their convective nature.[124] With few exceptions, long lines of cumulus development which might be expected in cases of squall lines are seldom seen. These matters are considered further in Section 8.1.1.

4.3.6 Stratus, Stratocumulus, Altostratus, and Altocumulus. Combinations of these types in two or more layers often occur and appear as a relatively bright amorphous sheet (Fig. 4-20). It is impossible to distinguish separate layers or the individual stratocumulus and altocumulus cloud elements, except that a slight cumuliform structure has been seen at the frayed-out edges of large overcasts (Figs. 4-8, 4-20). This altostratus and mackerel-sky altocumulus clouds have lower brightnesses. Overcast stratocumulus clouds appear quite bright (Fig. 4-24).

4.4 FURTHER CONSIDERATIONS

Application of the above discussions should be accompanied by an awareness of the following:

1. The use of the synoptic, airways and PIREP codes for reporting and obtaining cloud data entails a certain inevitable loss of information. Satellites represent a new and different observing system, and although observational language is so far largely in terms of the conventionally coded data it is felt that interpretation of cloud type from satellite pictures should not always be fitted into a classification admittedly inadequate to describe even the limited and discontinuous observations from the ground. The advantage of the essentially space-continuous satellite view should be kept in mind. The meso- and synoptic-scale parallel line structure, easily imaged and often seen in TIROS pictures, is an outstanding example of something not categorized within the international cloud classification. Interpretation of the cloud type is intimately associated with the pattern; the two combined often provide considerable information on the physical and synoptic processes taking place.

2. The parallel-line structure often seen seems usually to be oriented approximately with the circulation at the cloud level, but this is not always true, and caution is needed in such interpretation. Cases where lines of cloud are more nearly normal to the flow are frequently observed, as will be further discussed in later chapters of the report, and in Appendix C.

CHAPTER 5

A BIRD'S EYE VIEW OF THE KEY FEATURES OBSERVED

It is now a generally accepted concept that the individual cloud elements seen in a satellite picture, even when identified according to cloud type, present a lesser amount of useful information than is conveyed by the mesoscale, and synoptic and larger scale patterns into which the clouds are arranged. Therefore, any analysis which seeks to make maximum use of the satellite data should focus on these larger patterns. Accordingly, this chapter is intended to provide the reader with a brief overall summary of the key synoptic and larger mesoscale features and cloud patterns most readily noted and identified in satellite cloud pictures. This is to supply a view of the "woods" to prevent "getting lost among the trees"; more detailed discussions of each of the key cloud features will then be presented in subsequent chapters.

The term "key feature," as used here, represents any of the several types of cloud patterns which recur comparatively frequently, which can be identified with reasonable reliability, and which normally are so easily recognized that the eye of the analyst, after only a small amount of meteorological satellite experience, will automatically first be focused on them. In the sense of comparative prominence, such a feature is somewhat analogous to the role of a front or pressure center when a meteorologist first examines a newly received standard surface or upper-air chart.

The organization of the clouds into patterns is recognizable at all scales available from the pictures, ranging from fine patterns near the limit imposed by resolution to quasi-hemispheric features revealed only by the construction of mosaics of adjacent swaths of pictures or strips of nephanalyses. Because of the existence and great analytical significance of these larger scale patterns, there is much to be said for obtaining satellite cloud coverage over as large an area as possible. Full coverage of this sort is most necessary if the cloud field is being used as the basic analytic tool. At the other extreme of scale, that near the limit of resolution, the small scale patterns provide clues to the cloud types, as discussed in Chapter 4, and from them the stability and other characteristics of the air masses can often be deduced (see also Chapter 8).

5.1 RECOGNIZABLE CLOUD PATTERNS

Between these two extremes of scale, recognizable patterns include:

1. Spiral cloud patterns, usually referred to as cloud vortices, in a wide range of sizes. An example of one such vortex is shown in Figure 5-1.

2. "Comma" (') shaped cloud masses (Fig. 5-2), of sizes appropriate to the synoptic scale, having somewhat the appearance of vortices.

3. Major cloud bands (Fig. 5-3; Fig. 5-1, lower right portion), with and without distortions, bends, and bulges.

4. Major convective cloud masses (Figs. 5-4, 4-9, 4-10).

5. Large scale stratiform areas (Figs. 5-5, 4-16), often with a greater or lesser degree of patterned streakiness.

6. Synoptic scale areas more or less uniformly filled with essentially homogeneous smaller scale cloud patterns. These smaller scale patterns may include:
   (a) Convective cells of various sizes and shapes (Figs. 5-6, 4-11, 4-12).
   (b) Cloud bands and cloud streets (Figs. 5-7, 4-6).

These patterns are all discussed briefly in later parts of this chapter, and in some detail in later chapters of this report.

Unfortunately, a significant proportion of the cloudiness seen may not assume clearly recognizable patterns but exists as apparently unorganized, randomly positioned and shaped cloud masses at a wide variety of scales, such as that illustrated in Figure 5-8. The results of research and development activities will doubtless, from time to time, reveal further significant and recurrent patterns, within some of these apparently random cloud masses, which presently escape our examination. In the interim, it seems best when starting a synoptic analysis using the satellite data to concentrate first on recognizable patterns, some of which are nearly always present, and the synoptic features identifiable from them. When viewed in relation to the initial analysis thus provided, the interpretation of many of the apparently random cloud masses often becomes much clearer. As the analysis nears completion, all the cloud masses noted (whether in recognizable patterns or not) should of course be reviewed to insure that the final analysis is compatible with the observed data. Apparently random masses are also, of course, significant where a knowledge of existing or future cloud covered areas, as such, are themselves of operational significance.

Fig. 5-1 Spiral Cloud Pattern, or Cloud Vortex

Fig. 5-2 Comma-Shaped Cloud Mass

Fig. 5-3 Major Cloud Band

Fig. 5-4 Major Convective Cloud Mass

Fig. 5-5 Large Scale Stratiform Area

Fig. 5-6 Synoptic Scale Area of Convective Cells

Fig. 5-7 Synoptic Scale Area of Cloud Streets

Fig. 5-8 Unorganized, Randomly Positioned and Shaped Cloud Masses

Fig. 5-9 Family of Mid-latitude Cyclonic Vortices (From Reference 80)

5.2 LARGE SCALE CLOUD PATTERNS

On the largest, or quasi-hemispheric, scale of analysis, large masses of stratiform as well as cumuliform clouds show internal elongated and banded structures in the satellite photographs[76] and the "streaming" appearance of the earth's cloud cover is strikingly evident. Composites of pictures or nephanalyses covering a significant fraction of a hemisphere usually dramatically reveal the families of mid-latitude cyclonic vortices, such as that in Figure 5-9. Other examples are illustrated in Appendix B. The general sense of large-scale atmospheric motion is evident in such portrayals, clearly suggesting that some form of synoptic pattern in terms of major troughs and ridges can be deduced. Even the absence of widespread middle and high level cloudiness over certain regions can be synoptically meaningful if viewed in conjunction with those large cloud masses which can be interpreted.

The use of the satellite data at this scale of analysis will be further considered in Chapter 10 and Appendix B.

5.3 CLOUD VORTICES

Spiral cloud patterns occur in a wide variety of forms and scales in both tropical and extratropical regions. In temperate latitudes, the most conspicuous patterns are usually those related to major cyclonic storms (Fig. 5-1) which have begun to occlude or are in a subsequent stage of development or dissipation (see Chapter 6).

In the tropics, the major vortices (Figs. 5-10 and 5-11) are those associated with significant Tropical Storms, hurricanes, and typhoons, as will be discussed in Chapter 11. Significant tropical vortices may vary considerably in size, since tropical storms and hurricanes, and their related cloud vortices, may extend over either relatively small (Fig. 5-11) or significantly large (Fig. 5-10) areas and still be severe near the circulation center. While in general there is a fair correlation between the intensity of a tropical storm and the size of cirriform cloud shield associated with it, it is entirely possible to encounter a very intense non-steady state storm with a relatively small cirriform cloud canopy.[8]

Fig. 5-10 Super Typhoon

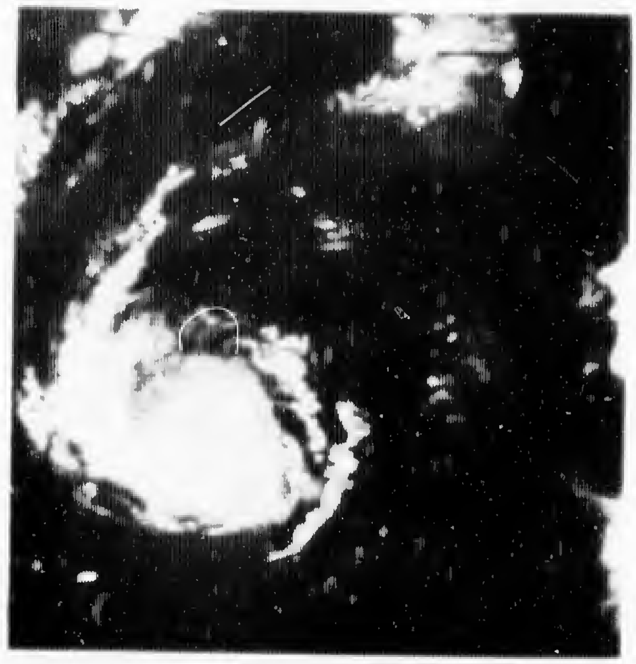

Fig. 5-11 Small Typhoon

Fig. 5-12 Vortex in Polar Air West of Major Cyclonic Circulation

Fig. 5-13 Comma-Shaped Cloud Mass Associated with Short Wave Trough

Fig. 5-14 Nearly Dissipated Major Storm System

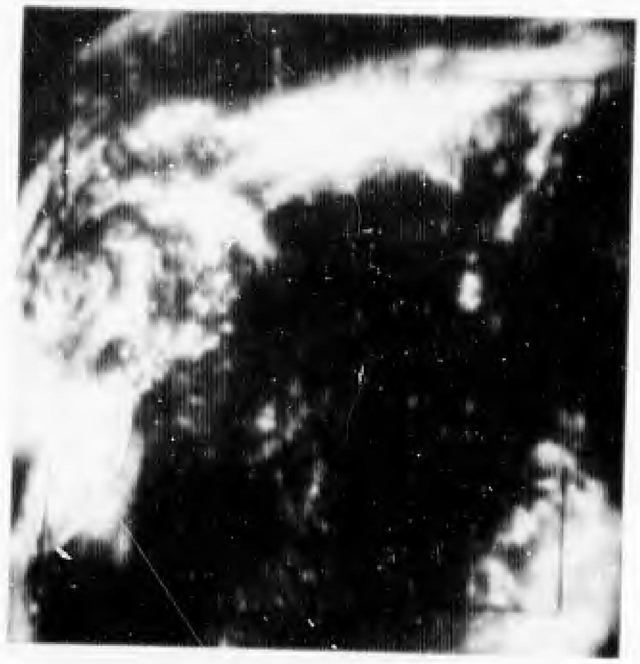

Fig. 5-15 Disturbance in the Easterlies of Less than Tropical S rm Intensity

Fig. 5-16 Tropical Upper Level System. (Note also Intensified Cumulus Activity over Cuba - to Left of Center Fiducial - as Compared to that over Immediate Surrounding Ocean)

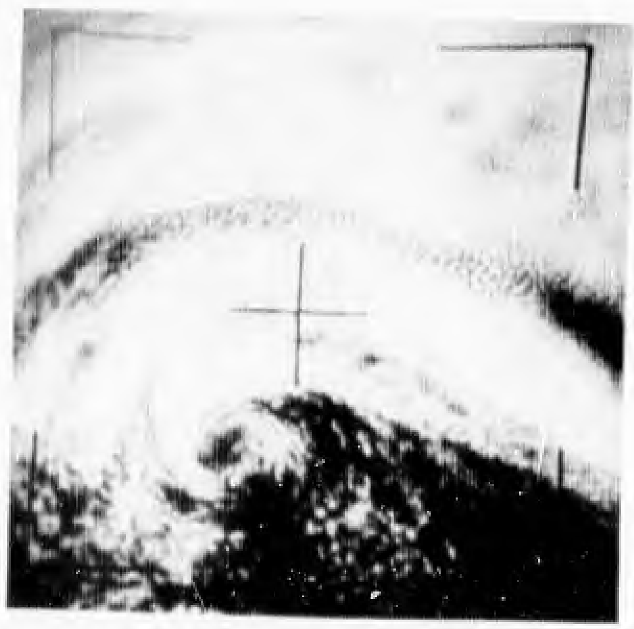

Fig. 5-17 Tropical Disturbance in Oceanic Monsoonal Trough

5.3.1 Lesser Vortices

It is also important to realize that many distinctive spiral cloud patterns may not be indicative of major cyclonic storms. Frequently, but not always, the size or apparent intensity of the cloud vortex provide clues to these cases; in other situations, the overall analysis deduced from the satellite and all available other data may indicate the nature of the vortex.

In extratropical regions, the most common of such patterns fall into three categories:

1. Smaller but often distinct cloud vortices (Fig. 5-12) found in polar air in extreme western portions of major cloud vortices and cyclonic circulations* (see Section 6.2.5.1). These appear to be associated with short wave upper troughs, and at the surface with a sharper trough or minor closed low. Significant storms may later develop from these disturbances as they move eastward around the major long wave troughs.[8]

2. "Comma" - or crescent-shaped cloud patterns of synoptic scale and with partial vortex characteristics (Fig. 5-13), which are formed by clouds in the eastern portions of short wave troughs and vorticity maxima, usually located equatorward and/or to the east of major upper troughs and closed upper level cyclones.[8]

3. Nearly dissipated major storm systems (Fig. 5-14), since in the final stages the vortex cloud pattern may suggest more intense circulation and weather conditions than actually exist.[61]

In the tropics, cloud patterns with some degree of vortex appearance are found associated with:

1. Various types of disturbances in the easterlies of less than Tropical Storm intensity (Fig. 5-15), as discussed in Section 11.4, which may or may not later develop into intense storms.[71]

2. Upper level systems (Fig. 5-16), which do not necessarily produce organized significant weather at the surface.[94]

3. Tropical disturbances which usually do not intensify beyond the early Tropical Storm stage (Fig. 5-17) and which tend to remain in, track along, and help maintain low level, monsoonal troughs over the tropical oceans.[96] These vortices

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* In the example shown in Figure 5-12, the major cyclone is beyond the horizon to the right (east) of the smaller vortex.

may appear to be secondaries[8] to more intense tropical storms which usually take a more poleward path out of the trough line.

In the stable eastern portions of subtropical high pressure areas, flow disturbances introduced by island terrain may also produce small but vivid vortex patterns (Fig. 5-18) in stratiform cloudiness[10,56] (see Section 8.2.8).

5.4 SYNOPTIC-SCALE COMMA- OR CRESCENT-SHAPED CLOUD PATTERNS

Bright, overcast, crescent-shaped cloud patterns, such as that shown in Figure 5-19, at times resembling in geometric outline and size cloud patterns associated with the first stages of occlusion of wave cyclones, have been found to be indicative of mid-tropospheric troughs. The clouds depict the area of upward vertical velocity ahead of the trough (see Section 6.2.3.1).

5.5 MAJOR CLOUD BANDS

While major cloud bands are usually of considerable synoptic significance, their correct interpretation often requires consideration of both surrounding cloud patterns and the larger scale synoptic analysis into which they are to be fitted. Major cloud bands are found associated with:

1. Cold and occluded fronts, currently or previously associated with a major cyclonic storm and on which other storms may later form (Fig. 5-20). Frontal cloud bands may persist in lower latitudes (Fig. 5-21) well after means to detect the front on a conventional basis have been lost.[102] Because of the normal relationship between the polar front and the jet stream, a jet stream will often be found just poleward of andessentially parallel to mid-latitude frontal cloud bands (see Chapters 6 and 7).

2. Convective instability or squall lines, particularly but not necessarily in the warm sector ahead of cold fronts. Such pre-frontal instability lines can at times be differentiated from a frontal cloud band by their more convective and broken appearance, and the related scalloped edges of the cloudiness forming the bands, as shown in Figures 5-22 and 7-1.

3. Post-frontal instability lines, including spiral bands, in vortices, west of the main frontal band (Fig. 5-23). These may often appear as secondary cold fronts in analyses based principally on conventional data.

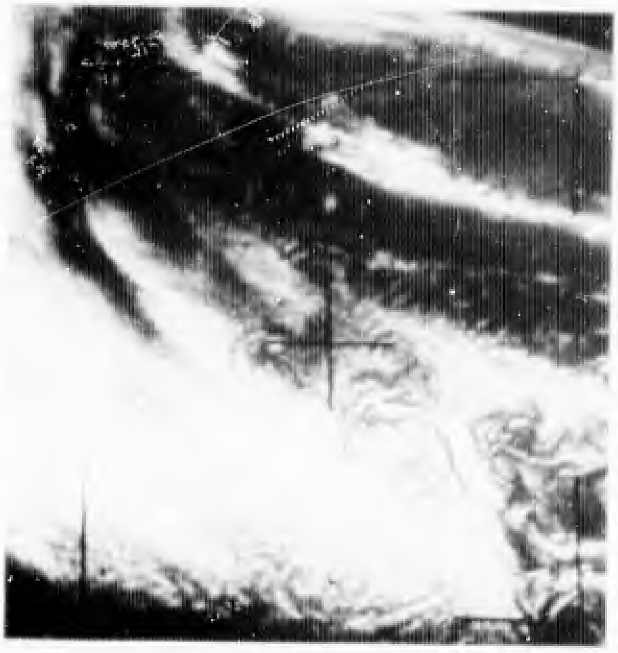


Fig. 5-18 Vortex Patterns Produced by Terrain-Induced Disturbances

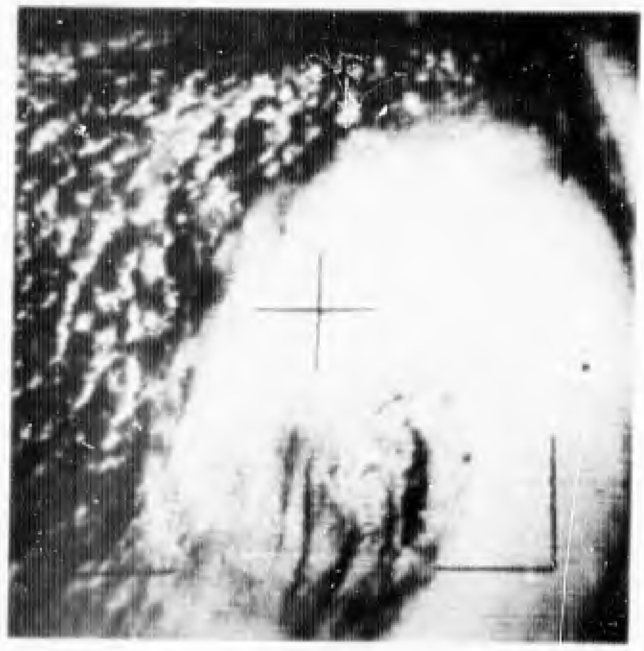


Fig. 5-19 Crescent-Shaped Cloud Mass

Fig. 5-20 Cloud Band Associated with Cold Front

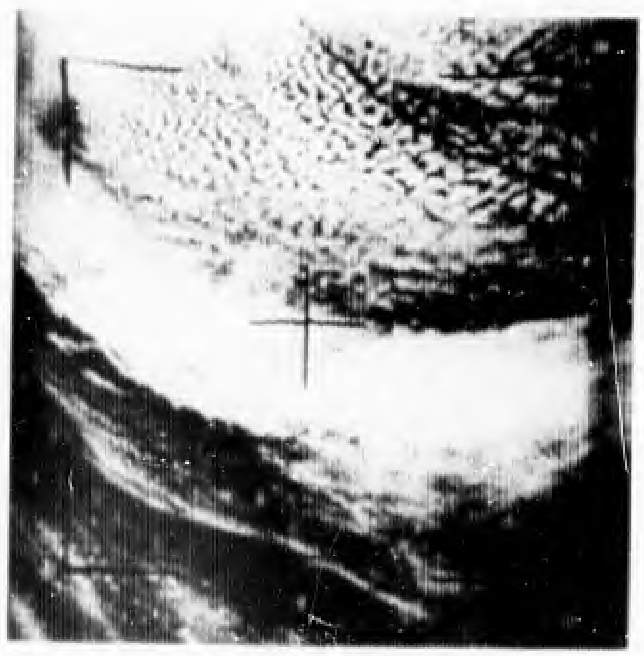


Fig. 5-21 Frontal Cloud Band at Low Latitudes

Fig. 5-22 Instability Line Ahead of Cold Front

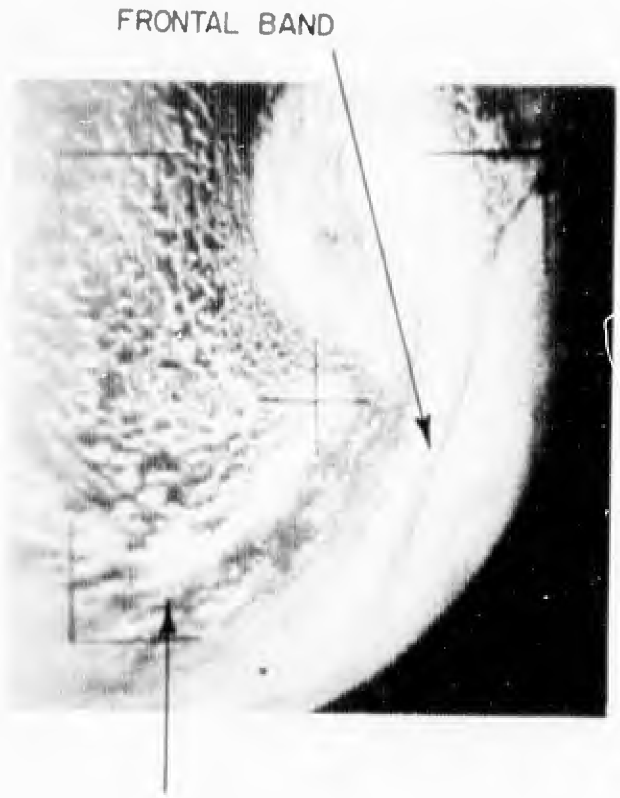


Fig. 5-23 Post-frontal Instability Line

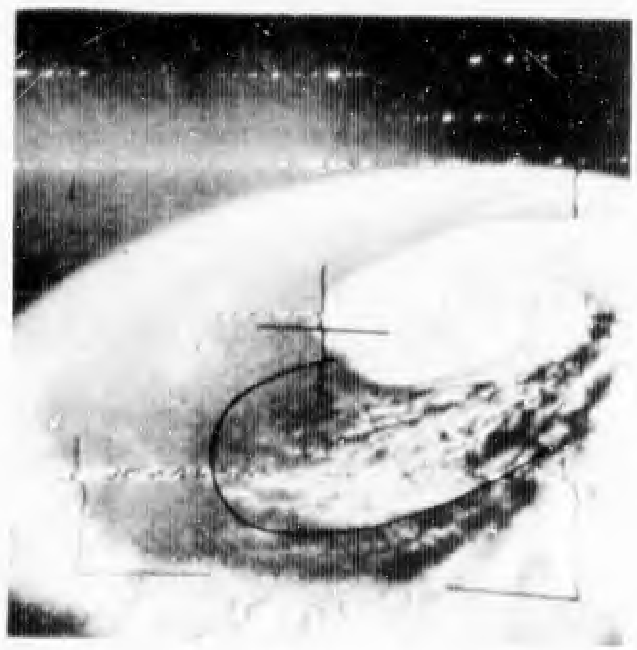


Fig. 5-24 Bands Associated with Spreading Out of Clouds Produced by Low-level Convection.

Fig. 5-25 Tropical Line of Major Convergence

4. The spreading out and merging of clouds produced by relatively strong but low-level convective activity in the cold air just behind and under a cold front (Fig. 5-24). In these cases, the vertical growth is inhibited, and horizontal spreading and merging promoted, by a strong lower tropospheric inversion. Positively differentiating such bands from cold fronts and post-frontal instability lines can at times be difficult. They are most usually found to the west of where the upper level trough crosses the frontal band.[81]

5. Tropical lines of major convergence (Fig. 5-25). These may result from either short term synoptic patterns, or from persistent features of the general circulation with the primary variations being seasonal in nature. These cloud bands and their convergence zones may be somewhat displaced from the center line of the trough with which they are related [96] (see Chapter 11).

Bending, bulging, or other distortions of a major cloud band (Fig. 5-26) should always be examined as a possible indication of incipient cyclogenesis. Formations of primary or secondary wave cyclones on a cold front (Figs. 5-26,-27-28)*, of secondary cyclogenesis on a prefrontal instability line, and of tropical disturbances on major tropical convergence bands (Fig. 5-29) are often first revealed by such features before they become apparent in other synoptic data (see Chapters 6 and 11). On the other hand, such cloud configurations have also been noted where no such synoptic significance could logically be inferred and without subsequent developments occurring. This points to the need for exercising caution in the interpretation of such cloud patterns, and the importance of applying all available data in the general vicinity.[8,9,71]

Long but relatively narrow cloud bands, at times giving a rather definite impression of being cirriform or at comparatively high altitudes (Fig. 4-14), may be indicative of a jet stream just poleward of their location. At times such bands become apparent from the shadow they cast on lower level cloud masses (note left end of bands in Fig. 4-14). Such bands may be particularly useful in locating the position of the jet stream where it cuts across lower level flow patterns (Fig. 5-30), and across patterned cloud masses at lower levels (see Chapter 7).

* Because of the limitations to TIROS coverage, as discussed in Chapter 2, it is rare to be able to follow an incipient wave cyclone as it develops. The case shown in Figure 5-26 was an exception, and two subsequent stages, as observed 24 and 48 hours later, are shown in Figures 5-27 and 5-28. This sequence of development will be further discussed in Chapter 6.

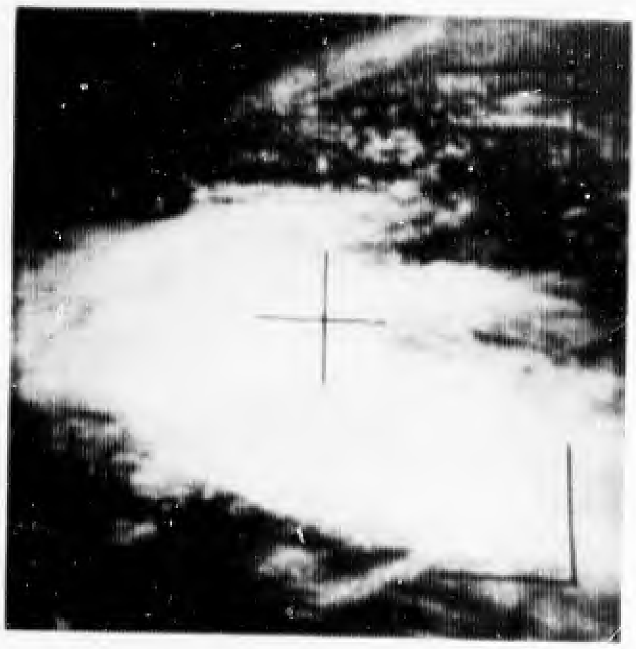


Fig. 5-26 Wave Cyclone on Cold Front (See also Figures 5-27 and 5-28)

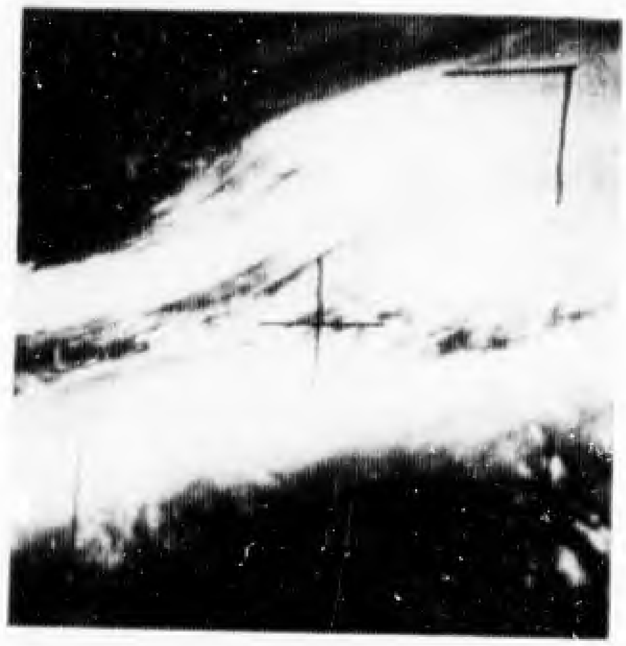


Fig. 5-27 Beginning of Occlusion Stage of Storm Shown in Figure 5-26

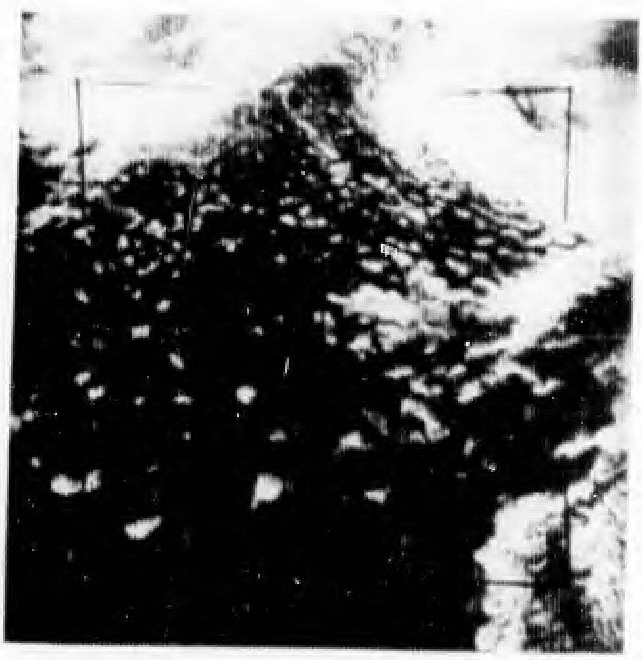


Fig. 5-28 Occluded Mature Cyclone Stage of Storm Shown in Figures 5-26 and 5-27

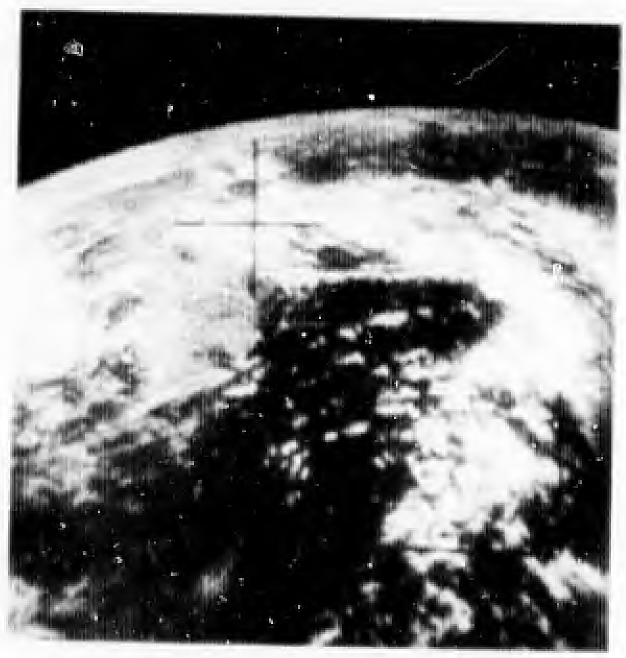
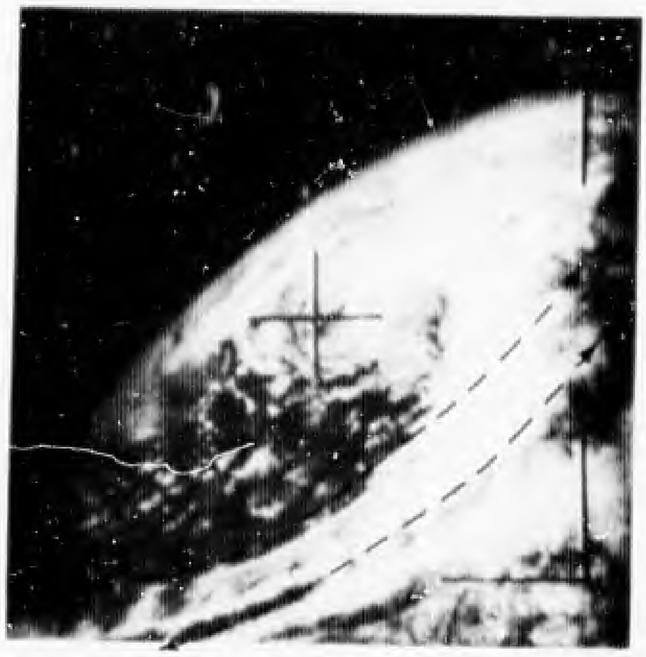


Fig. 5-29 Formation of Tropical Disturbance - Bending of Tropical Convergence Band



OVERLAY LINES ENCLOSE AREAS SLIGHTLY LARGER THAN CLOUD FEATURES TO AVOID OBSCURATIONS

Fig. 5-30 Cirrus Bands Indicating where Jet Stream Crosses Lower Level Cloudiness

5.6 MAJOR CONVECTIVE CLOUD MASSES

As has been mentioned in Chapter 4 in relation to the identification of cumulonimbus clouds and thunderstorms, and will be further discussed in Chapter 8, major convective cloud masses (especially if bright, with sharply defined borders, and separated or isolated from other cloud cover) should be suspected as producers of locally severe weather. Less severe but still significant weather is likely where such major convective cloud masses are apparent but imbedded in more extensive cloud cover. Examples of such convective cloud masses have been shown in Figures 4-6 (upper left), 4-9, and 4-10.

5.7 LARGE SCALE STRATIFORM AREAS

Such cloud cover is frequently observed in those areas where it is synoptically or climatologically to be expected. Examples include the stable eastern portions of the subtropical anticyclones, as in the eastern North Pacific off Baja California (Fig. 4-16) and in the eastern North Atlantic off North-west Africa (Fig. 5-5); and stratus north of the Gulf of Mexico (Fig. 7-2) with stable conditions and south winds during the winter season.[52]

West coast stratus appears to be considerably more streaky and patterned than would have been anticipated prior to the availability of the satellite data,[126] as can be seen in Figure 4-16.

5.8 SYNOPTIC SCALE AREAS WITH HOMOGENEOUS SMALLER SCALE PATTERNS

Considerable information is provided by areas of synoptic dimensions more or less uniformly filled with scattered to broken cloudiness in distinct and rather homogeneous mesoscale patterns. Some examples of such conditions were included in appropriate parts of the discussion of cloud type interpretation (Chapter 4).

In this category of key features can be included:

1. Cellular convective cloudiness found under inversions in the flow to the rear of major cyclones, especially over the oceans (Fig. 5-6). In such areas, the analyst can deduce low level instability (usually from cold air flow over a warm surface), sufficient low level moisture for cloud formation, and often a capping inversion at levels normally several thousand feet above the surface.[62] Detailed

examination of the mesoscale patterns can often provide estimates of the relative low level stability, the strength or height of the inversion, and/or the low level wind velocity[70] (see Sections 7. 2. 1 and 8. 1. 2. 2).

2. Mesoscale lines, streets, and bands of cumuliform clouds (such as that in Figure 5-7), which may display orientations parallel (Fig. 5-7) or perpendicular (Fig. 4-6) to the wind, or to the vertical shear of the horizontal wind (see Chapter 8).

3. Lee waves (Fig. 4-13) and other orographically produced mesoscale cloud patterns (see Section 8. 2).

EXTRATROPICAL
VORTICES

CHAPTER 6

EXTRATROPICAL VORTEX INTERPRETATION*

The most vivid patterns noted in extratropical latitudes are the cloud vortices. The principal features of these vortex cloud patterns are sufficiently recurrent to permit the approximate stage of cyclonic development to be deduced in most cases. The cloud depiction practices used in the preparation of the nephanalyses have been found to be adequate to permit the approximate stage of storm development to be recognized in the majority of cases. Estimates of pressure center positions, pressure departures from normal, future system movement, frontal positions, air mass conditions, surface and upper level winds, and precipitation can also be inferred from the cloud patterns visible in the satellite pictures. Some of this information is available from the patterns as reproduced on the nephs; other features are commonly interpreted at the readout stations and such interpretations explicitly entered on the nephs.

6.1 A CONSIDERATION OF SYNOPTIC CONCEPTS

This chapter and some portions of Chapter 7 have been formulated, to a major degree, in terms of the more traditional synoptic concepts, with air masses and frontal systems serving as the primary synoptic reference features. This emphasis has resulted from two causes:

1. The synoptic background of the principal author of these chapters, which had been primarily along air mass and frontal lines.

2. The fact that the very great majority of published synoptic studies with regard to meteorological satellite data have emphasized the traditional approach. While a few studies have included,[11, 130, 133] and in some very limited cases emphasized,[12, 93] such modern synoptic concepts as vorticity advection and related vertical motions, in many such cases the correlations with the cloud patterns

* Much of this chapter is essentially a condensation of material originally published in References 8 and 127.

appeared to be somewhat marginal.*

After the initial drafts of these chapters had been prepared, it was suggested** that the comparative disregard of modern concepts was both unfortunate and unnecessary. However, it was found that reformulation to include full discussions from the most modern viewpoint would be impractical because of the lack of suitable definitive studies. As an alternative, this section has been added and will summarize certain aspects of existing synoptic knowledge which seem to be closely related to synoptic scale cloud patterns as seen by the satellite. Furthermore, briefer but more specific discussions of these and related points have been included in appropriate parts of this and the next chapter, and in Chapter 10.

6.1.1 Correlations between Cloud Cover and Synoptic Scale Vertical Motions

One should expect a good correlation between the synoptic scale cloud features observed by satellites and vertical motions computed for areas with diameters of the order of 100 miles and at levels 100 mb apart. These correlations should be particularly good in the middle and subsequent stages of a cyclone's life cycle. Early in the lifetime of a cyclone, the moisture structure is principally the result of previous conditions; in some cases or in some portions of a particular storm, the air may be too dry to produce significant cloudiness even with relatively pronounced upward vertical motion. As the storm approaches maturity and increases in size, it is better able to organize a characteristic moisture field.

For instance, in a small young cyclone, a region of strong ascent may still be unsaturated and cloud-free whereas, in a fully developed large occlusion the center of ascent is likely to be cloudy because even relatively dry air entering the storm will be raised to saturation before reaching the center of ascent. Accordingly, the precise relation of cloud boundaries to the boundaries of the areas of ascent and descent may vary from case to case in relation to the moisture conditions of the system.

* Review of these studies in terms of other synoptic studies which did not use satellite data[61, 98] suggest the poor correlations may well result from primary use of NWP products for a single level (which provide only gross resolution values) and the frequent assumption of a direct relationship between vertical motion and vorticity advection alone, rather than from any basic flaws in modern synoptic concepts.

** By Dr. Carl W. Kreitzberg of AFCRL, for whose assistance in this area and during the drafting of this section the authors are most deeply appreciative.

6.1.2 Vertical Motion Diagnosis From Standard Synoptic Parameters

It has been shown[98] that for synoptic and larger scale motions (where an assumption of geostrophic conditions is reasonable) the vertical motion of the air except very near the surface is determined, for practical purposes of analysis, as the algebraic sum of two effects:

1. The rate of change in the vertical of the advection of vorticity*.
2. The rate of advection of temperature (or the rate of advection of the thickness of a layer).

Advection of course occurs when the wind has a component across an isoline of vorticity, temperature, or thickness.

Considering first the effect only of the advection of vorticity, if there is an upward increase of cyclonic vorticity advection it will tend to be accompanied by upward vertical motion. Upward vertical motion will also be associated with an upward decrease of anticyclonic vorticity advection. Similarly, an upward increase of anticyclonic advection, or an upward decrease of cyclonic advection, tends to be associated with downward vertical motion. For those interested more detailed explanations of these relationships are available in References 85 or 98. Since the vorticity advection near the surface is usually small, the vorticity advection in the middle troposphere (say, as shown by the 500 mb chart) usually determines the vertical change of vorticity advection. Accordingly, positive (cyclonic) vorticity advection at 500 mb is usually accompanied by upward vertical motion, and vice versa.

Considering now the effect only of temperature or thickness advection, in a region of warm advection (wind blowing from warm to cold air, or toward a region of lesser thickness, and so veering with height), vertical motion will tend to be upward. Similarly, in a region of cold advection (wind blowing from cold to warm air, or toward a region of greater thickness, and so backing with height), vertical motion will tend to be downward. Again, fuller explanations are available in References 85 or 98.

* For those who dislike the precise hydrodynamical terms, vorticity can be thought of as a combination of the horizontal shear, and the curvature of the streamlines.

6.1.3 Application to Some Synoptic Models

Cyclonic vorticity centers are usually associated with closed lows or troughs, but strong horizontal wind shear, such as is found on the poleward side of the jet stream, can contribute substantially to the location and magnitude of the vorticity centers. Closely related to such lows, troughs, and wind shear zones is usually a frontal zone (or a somewhat broader baroclinic zone) in the middle and upper troposphere, characterized by near parallelism of isotherms and streamlines. An idealization of this type of zone is presented in Figure 6-la. Here the isotherms and contours are exactly parallel; the thickness advection vanishes but the rapid upward increase of wind speed produces a marked increase in the magnitude of the vorticity advection up to the level of the core of the jet stream. Above this level the wind speed and the vorticity advection weaken rapidly in the lower stratosphere,[98] but because of the lack of stratospheric clouds this is of little concern as regards interpretation of the satellite pictures.

The associated patterns of vertical motion due to vorticity advection, shown in Figure 6-1b, represent the total vertical motion in this case. Between the ridge and the next downstream trough the upward increase of anticyclonic vorticity advection produces descent below the level of the jet core. The descent is particularly intense in the frontal zone where the vertical wind shear is strong. (Above the level of the jet core the decreasing anticyclonic advection is associated with ascent). Between the trough and the next downstream ridge a similar picture is found, with reversal of the signs of the vorticity advection and of the vertical motion. Here maximum ascent occurs within the strongly baroclinic zone.[98]

In the lower atmosphere there is often a pronounced component of air flow normal to frontal zones, so that strong temperature advections occur. In these levels the vorticity advection fields are weakly developed because of the relatively small wind speed. An idealized low-level cyclone is shown in Figure 6-2, along with the patterns of vertical motion accompanying its frontal structure. The cold front is associated with descent and the warm front with ascent. This picture roughly resembles the classical view of fronts but places the strongest vertical currents within the transition zones separating the air masses, while in the traditional concept the main vertical motions occur in the air masses, near the interface which separates them.[98]

Actual case study computations[98] have shown that the thermal advection effect on vertical motion is indeed primary at low and lower middle tropospheric levels. Ahead of a surface cyclone and to the east of the upper level trough, ascent exists at low levels. Behind the cold front and to the west of the trough aloft, descent in the cold air mass predominates at low levels, although surface heating here may produce convective ascent and scattered to broken low level cloudiness.

The vorticity advection effect, as expected, predominates in middle and upper tropospheric levels. When an upper trough is not associated with a low-level frontal system, the vorticity effect alone can produce upward vertical motion and cloudiness ahead of the trough, with downward motion and clearing to the rear. When any associated front is quasi-stationary, the vorticity effect can dominate the vertical motion field but, with moving intense frontal zones, the temperature advection effect will dominate the lower troposphere.

In the middle troposphere, combined positive vorticity advection and positive thermal advection can produce substantial ascent in the warm frontal cloud shield. When the temperature trough is lagging behind the pressure and vorticity trough, rapid descent is to be found in the region of combined cold advection and negative vorticity advection. Behind the surface cold front one can often expect to find descent in the lower troposphere, associated with the cold advection, coexisting with ascent in the middle and upper troposphere ahead of the 500 mb trough. Some of these effects are shown in the idealized model of Figure 6-3.

A specific case study[98] of the field of vertical motion in relation to the sloping tropospheric baroclinic zone associated with a developing cyclone indicated a number of such recurring relationships between the two. Prominent centers of ascent and descent occurred as low as 900 mb and as high as 400 mb. These tended strongly to occur within the baroclinic zone rather than in the adjacent air masses. In the upper troposphere, descent occurred in that portion of the baroclinic zone west of the cold trough. The area of subsidence was invaribly centered within the zone above the 600-mb level and was attributable to the rapid upward increase of anticyclonic vorticity advection which occurs here. The vertical motions in the portion of the baroclinic zone ahead of the cold trough were more complex. Ahead of the surface wave cyclone, warm advection at low levels combined with an upward increase of cyclonic vorticity advection to produce regions of ascent typically centered below 600 mb. Immediately to the rear of the surface cyclone, on the other hand, cold advection was sufficiently strong to produce a maximum of descent at or below 800 mb, while an upward increase of cyclonic vorticity advection in the

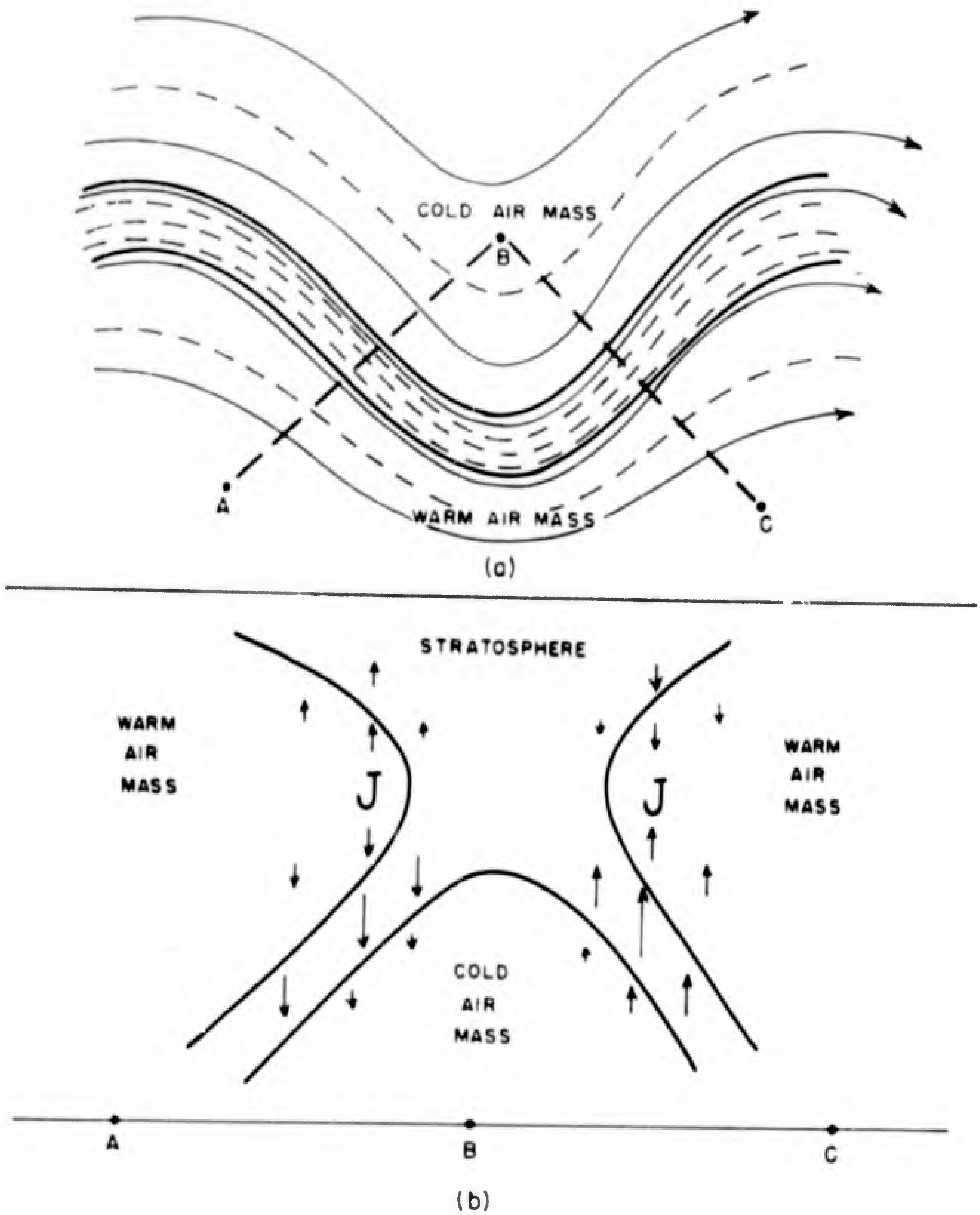


Fig. 6-1 a) Contours (Solid) and Isotherms (Dashed) for Idealized Frontal Zone in Middle or Upper Troposphere. Heavy Solid Lines are Boundaries of the Baroclinic Zone.

b) Vertical Cross-section of Vertical Motion Due to Vorticity Advection Associated with Frontal Zone in Part (a) of this Diagram. The Approximate Position of the Jet Core is Indicated by the Letter "J". (From Reference 98)

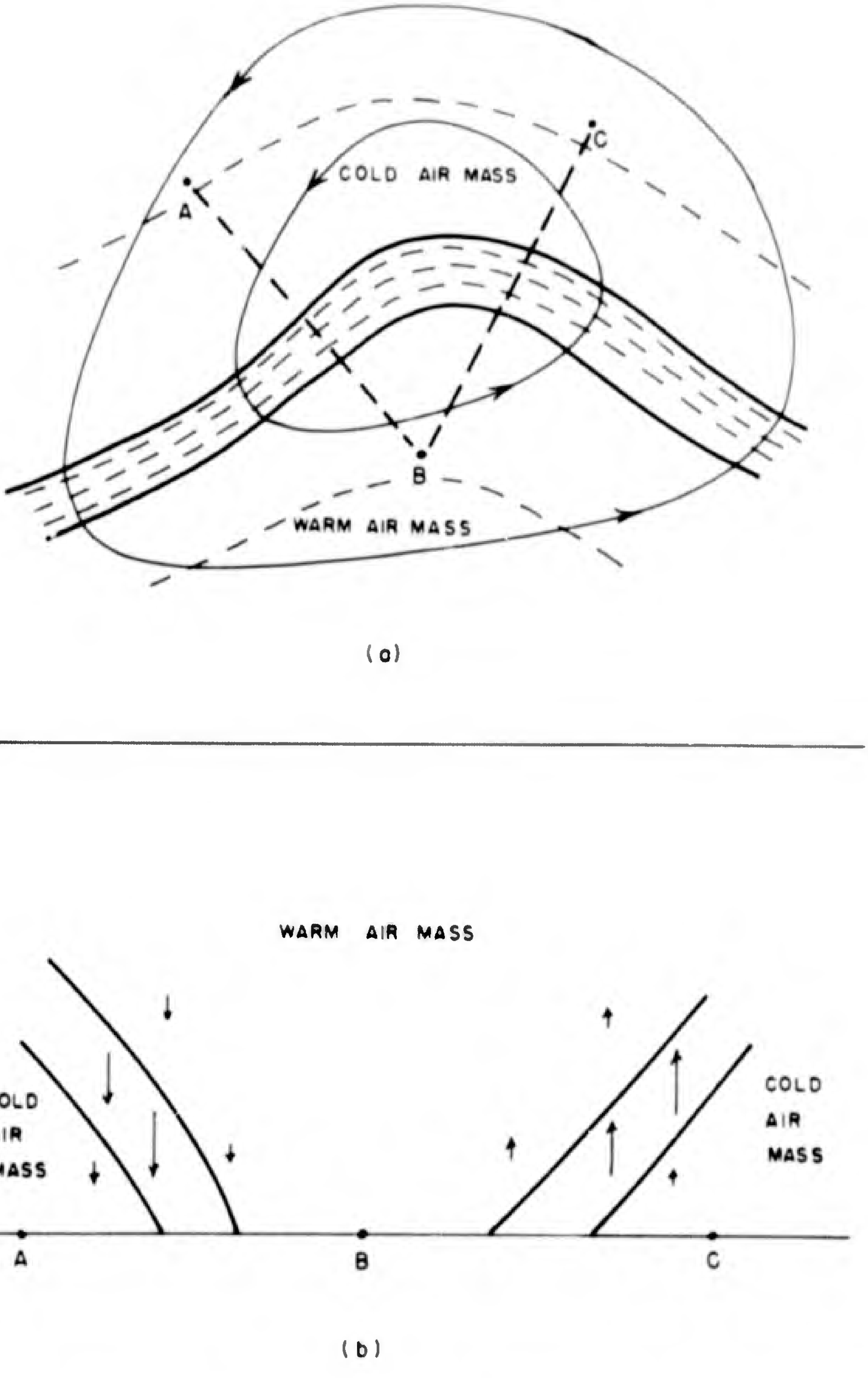


Fig. 6-2 a) Contours (Solid) and Isotherms (Dashed) for Idealized Frontal Zone in the Lower Troposphere. Heavy Solid Lines are Boundaries of the Baroclinic Zone.
b) Vertical Cross-section of Vertical Motion Due to Thermal Advection Associated with Frontal Zone in Part (a) of this Diagram. (From Reference 98)

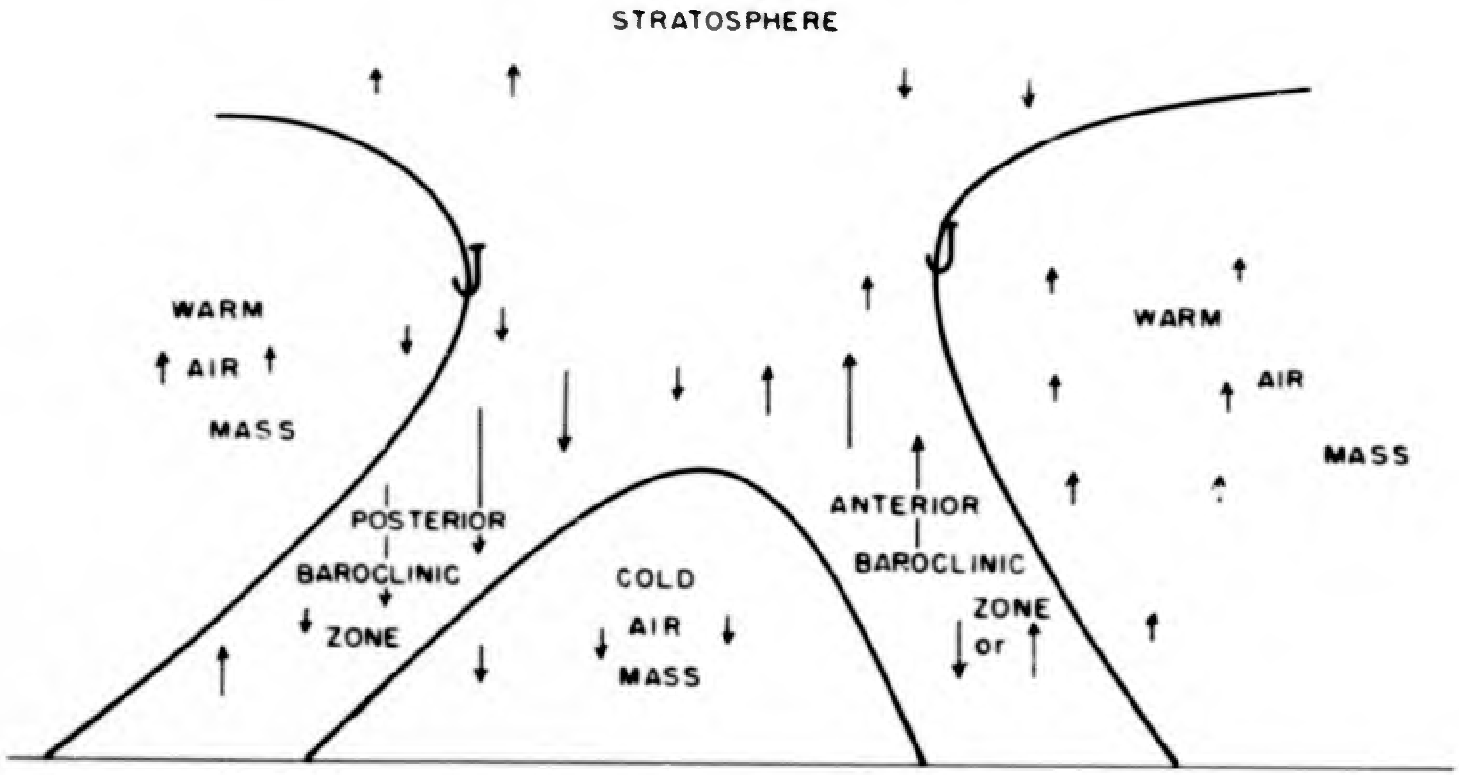


Fig. 6-3 Idealized Model of Vertical Motions, Air Mass and Baroclinic Structure Associated with a Large-Scale Trough in the Middle and Upper Troposphere (From Reference 98)

high-level portions of the baroclinic zone was sufficient to produce a center of ascent at 500 mb or above.

The cloud structure was generally in good agreement with the computed vertical motions; the regions of strong descent were almost completely free of clouds in the middle and upper troposphere, while occurrence of extensive stratiform clouds extending into the upper troposphere tended to coincide with major updrafts at these levels.

Discrepancies were observed, however. Cloud systems in the early phase of the storm were incompletely developed evidently because of lack of moisture. Once formed, an area of cloudiness may persist for some time after upward vertical motion stops and possibly even after weak downward motion begins. Cloud systems as well as vertical motion patterns were particularly complex in the portion of the baroclinic zone between the upper trough and the surface cyclone center. The details of the two patterns failed to coincide, however, and it is evident that advection of dry air with a history of descent from the rear of the upper trough is as important as the local vertical motion in determining the cloud structure. Low clouds were not well related to the computed vertical motion, since convective and turbulent processes near the surface obscure the effect of the large-scale vertical drafts. Unfortunately, this case occurred prior to the launch of TIROS I and similar computations for a case with satellite data are not yet available.

These results and those of other case studies[61] suggest that, while fronts and low level air mass properties may be significant to conditions in the lower layers of the troposphere, much of the cloudiness associated with extratropical synoptic scale features and observed from satellites is more closely associated with synoptic scale vertical motion fields as described above.

6.1.4 Larger Scale Mid-Tropospheric Vertical Motions

Based on the same principles as those discussed in Section 6.1.2, vertical motions are frequently computed for a single level in the middle troposphere, each data point representing the average value of the vertical motion over an area of the order of 300 miles in diameter. Characteristic magnitudes are 5 cm/sec or less. Such charts are routinely produced, on both a diagnostic and a forecast basis, by the NWP unit at NMC and transmitted by facsimile.

In such large scale, mid-tropospheric vertical motion charts, general descent is normally found between the ridge line and the downstream trough, while general ascent is found from the trough line to the next downstream ridge line. Centers of peak ascent and descent are found nearly midway between the ridge and trough lines and near the latitude of the maximum wind at the 500 mb level.

These large scale vertical motion patterns are roughly associated with the typical large scale areas of stratiform or cumuliform cloudiness ahead of troughs, and with a minimum of cloudiness behind the troughs. However, an exact match between vertical motions as computed on this scale for a single level and the cloudiness observed by satellites is hardly to be expected, and has not in general been found.[11, 12, 130, 133] This can be partly explained by the variations in the vertical motion fields at different levels, as found when higher resolution, multiple level computations were made;[98, 109] such computations were discussed just previously.

6.1.5 Vertical Motions at the Larger Mesoscale

Vertical motions on the 50 mile scale can be inferred from the cloud bands observed on this scale, and they have been computed in a few cases.[27, 61] There may be several cells of ascent and descent in a cross section through a frontal system, with vertical velocities on the order of 40 cm/sec. These cells appear to be about 200 mb in depth, and to be about 50 miles in width normal to the frontal zones. Such cells can be associated with cloud and precipitation bands, with multiple and secondary fronts or convergence zones, and with multi-layered cloud structures. Much research remains to be done before vertical motions on this scale are known and understood as well as the larger scale vertical motions.

The cloud patterns associated with this scale of vertical motions should be visible in the satellite pictures when not obscured by more continuous and/or higher altitude cloudiness.

6.1.6 The Primary Synoptic Approach of This Chapter

The following discussion approaches vortex stage description from the viewpoint of a development sequence starting with a wave on a front,[9] as shown in Figures 5-26, -27, -28. It is recognized that while many cyclonic storms and their associated cloud vortices may evolve from a frontal wave, a significant number do not.[61, 83, 99, 110] Many cyclones form from an upper air vorticity maximum and the intensification of a short wave upper trough moving through a planetary scale trough. In such cases, the frontal wave concurrently shown in a conventional surface analysis is often nothing more than a depiction device, since low level frontogenesis may well follow rather than precede cyclogenesis. Accordingly, the first recognizable cloud pattern may be similar to any one of the first four stages described below.

It is also well to keep in mind the possibility of limited surface development taking place, without formation of a cloud vortex, in the absence of a significant upper air trough or closed low.

6.2 A VORTEX DEVELOPMENT SEQUENCE

6.2.1 The Frontal Wave Stage

When cyclogenesis initiates as or in association with a frontal wave, it can at times be detected as the broadening or bulging of the frontal band. Typically this is accompanied by slightly curving parallel bands poleward of the front, and a more reflective area of higher and deeper clouds just to the east of the wave crest, as shown in Figure 6-4.[9, 12]*

At this stage, the development is so meager that very similar cloud configurations have also been found where neither wave nor front could logically be inferred, pointing to the need for exercising caution in the interpretation of cloud patterns. On the other hand, also as a corollary to the relatively insignificant appearance of this stage, the wave may often be hidden by a more extensive cloud sheet.[9] This is illustrated in Figure 6-5.* In any event, no visible distinct spiral pattern is to be expected at this stage.[12, 44] Even so, the development may not be apparent in the synoptic data until twelve hours after the bulge on the front can be discerned in the satellite pictures.[67] At this stage, the development can be expected to be influencing only conditions near the surface and in the very lowest portions of

* In Figures 6-4, -5, -6, -7, -10, etc., the sketch is an idealized schematic and <u>not</u> a neph of the photographic example.

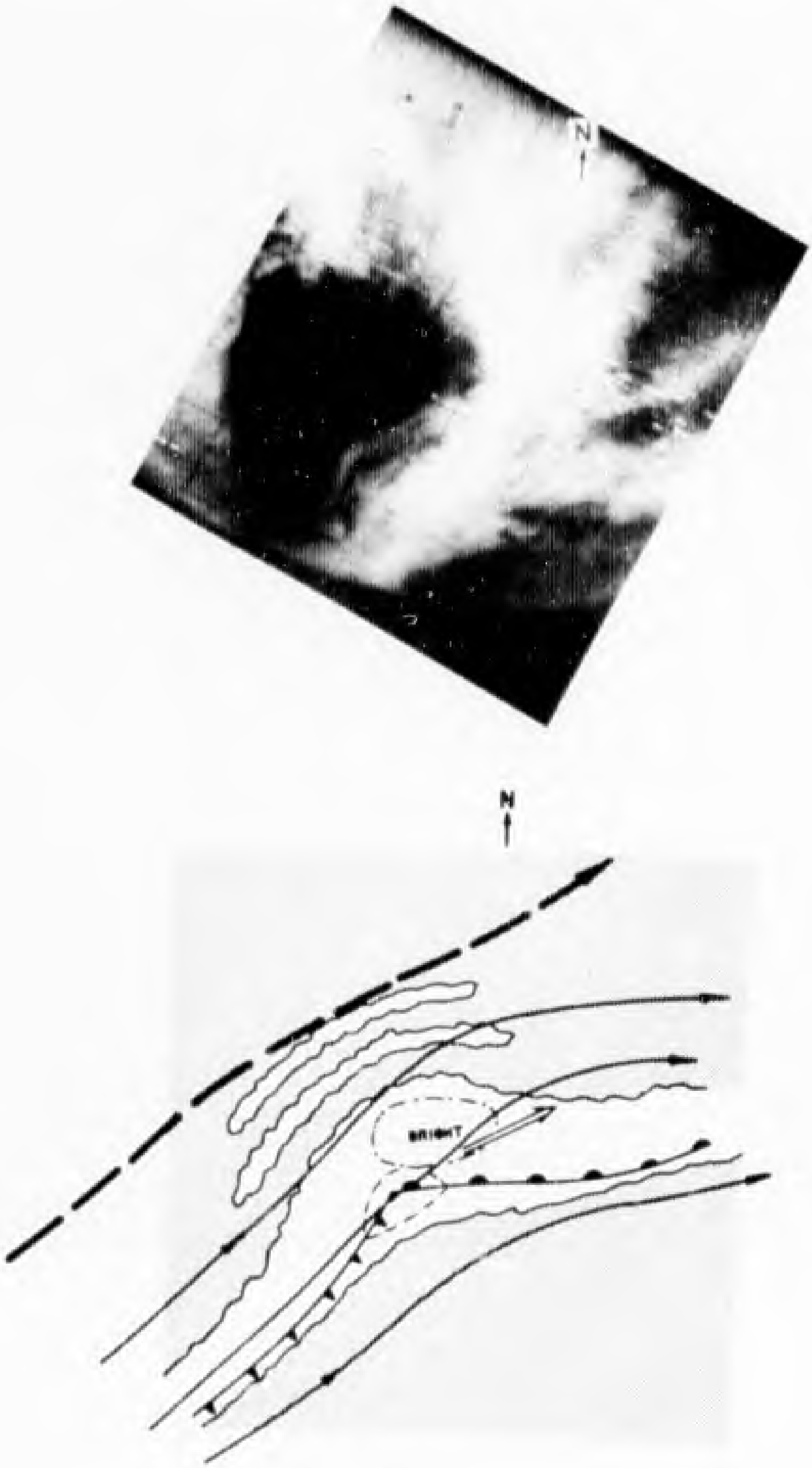


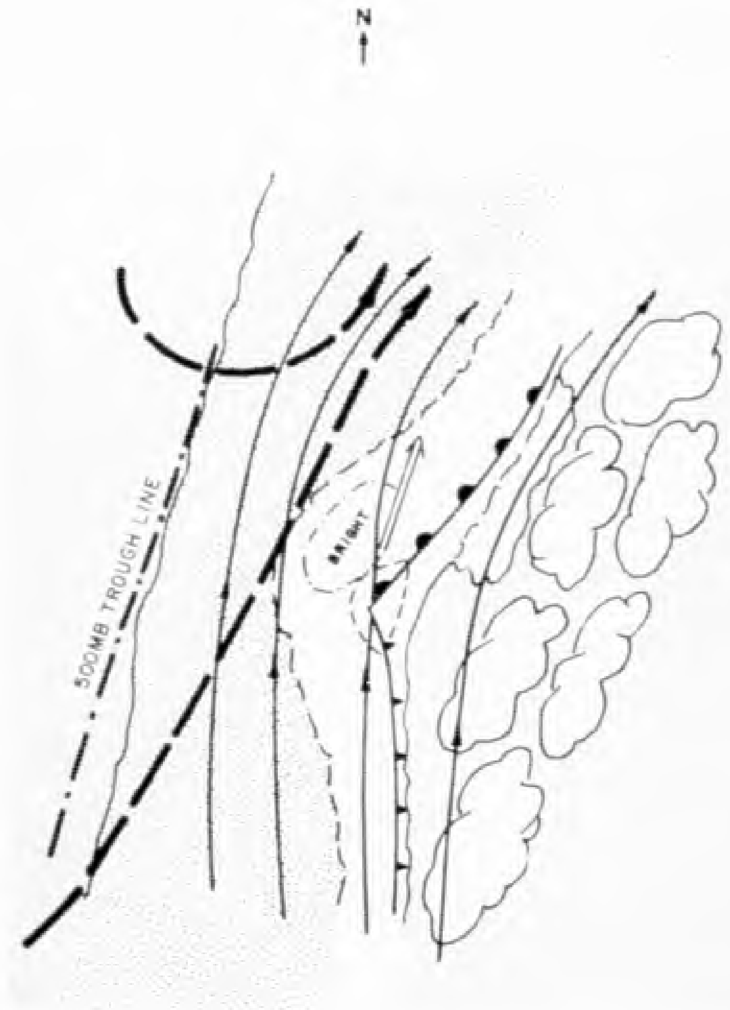
FIGURE LEGEND

— CLOUD

— LAND AND OCEAN

DASHED LINES — LOWER TROPOSPHERE FLOW
HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW
SOLID LINE — MIDDLE TROPOSPHERE FLOW
DOUBLE SHAFT ARROW — DIRECTION OF SYSTEM MOVEMENT

Fig. 6-4 Frontal Wave



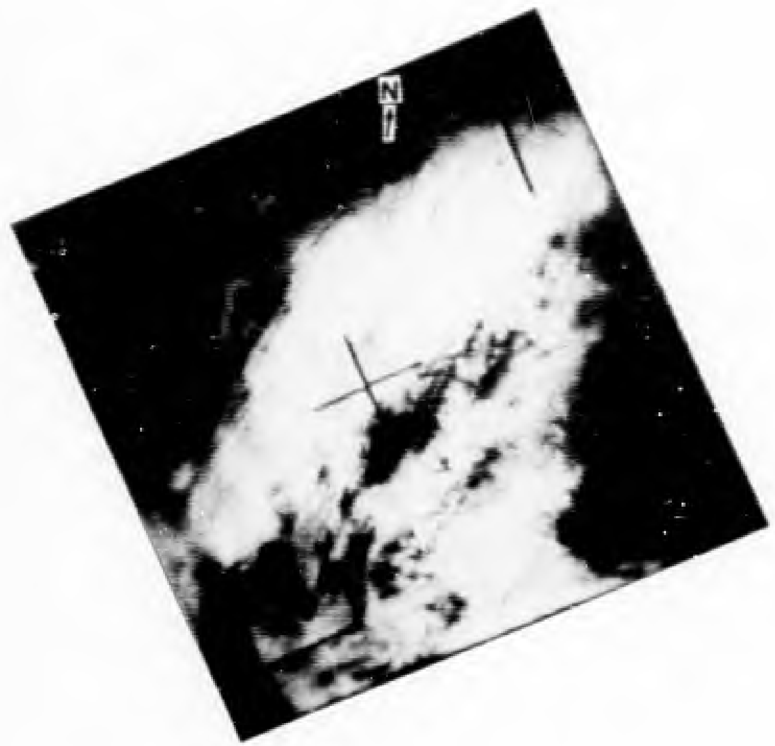


FIGURE LEGEND

— CLOUD

— LESS REFLECTIVE CLOUD

— LAND AND OCEAN

DOT–DASH LINE — TROUGHS AND RIDGES

DASHED LINES — LOWER TROPOSPHERE FLOW

DOUBLE SHAFT ARROW — DIRECTION OF SYSTEM MOVEMENT

HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW

SOLID LINE — MIDDLE TROPOSPHERE FLOW

Fig. 6-5 Cloud-masked Frontal Wave

the atmosphere, except to whatever extent a pre-existing short wave trough moving over the front may have been responsible for inducing the development.

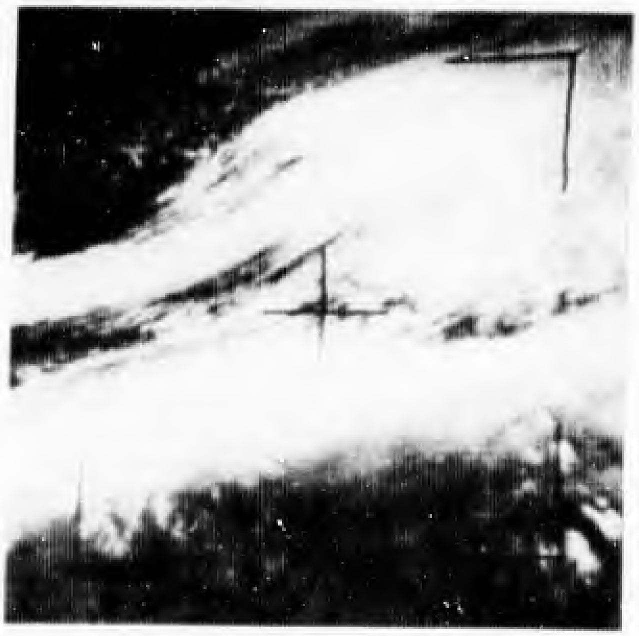
If the field of view of a satellite pass does not include the center of an area of probable development equatorward and to the west of a major cyclone, evidence of any such developments may sometimes be noted near the edge of the photographed region in the form of a significant and otherwise unidentified cloud band or poleward extension of an existing band.[133]

In summary, pictures of areas synoptically and/or climatologically prone to cyclogenesis should be carefully examined for signs of wave development, whereas cloud patterns possibly indicating wave development outside such areas should be reviewed carefully in terms of other available data before being accepted on face value without other substantiating evidence. Furthermore, the possibility of an incipient wave dying out or of a stable wave moving along a front without significant increase in amplitude must always be considered. These waves usually have little or no upper level support in the form of a vorticity advection area.

6.2.2. Pre-occlusion Stage

As we proceed to the subsequent stages of development, it must be realized that a continuity of progression, rather than discrete stages with precise boundaries, is to be expected in any storm development model. Accordingly, any attempt to arbitrarily distinguish between an advanced phase of one stage and an early phase of the next stage is impossible and has no real meaning.

The transition from the wave to the partly occluded vortex is rapid and, consequently, only infrequently observed.[9] Nevertheless, it seems desirable to discuss a stage of development between the frontal wave pattern and the stage depicting the beginning of the occlusion process.[70] This cloud pattern, illustrated in Figure 6-6, shows a thick line of cloudiness lying poleward from the low pressure center of the open wave stage. There may be a faint ring of cellular clouds surrounding the leading edge of bright clouds, appearing almost to be a reef of clouds in front of the entire wave structure.[67] Perhaps the key feature of this stage is the significantly greater poleward bulging or cloud protuberance than in the frontal wave stage, retaining generally a longitudinal symmetry which disappears in the succeeding Beginning-of-Occlusion stage as the intrusion of the clear, dry air first becomes apparent.



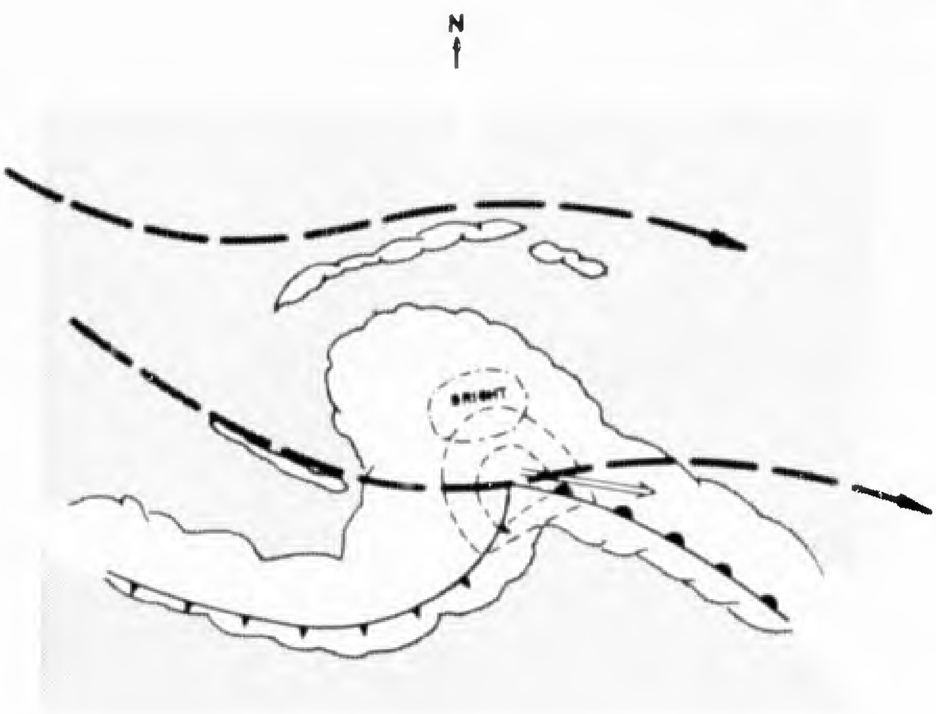


FIGURE LEGEND

☐ — CLOUD

☐ — LAND AND OCEAN

DASHED LINES — LOWER TROPOSPHERE FLOW   DOUBLE SHAFT ARROW — DIRECTION OF SYSTEM MOVEMENT
HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW

Fig. 6-6 Pre-occlusion

At this stage, the closed cyclonic circulation would in a typical case be principally influencing the lower atmosphere, but not yet reaching significantly to the 500 mb level. The ill-defined circulations of this stage typically indicate a system having a pronounced vertical tilt, and little or no closed circulation aloft. [12]

6.2.3 Beginning of Occlusion Stage

This stage is still within the period of rapid development and observations appear to be scarce. There is now a noticeable asymmetry in the cloud pattern, as shown in Figure 6-7, due to the intrusion of the clear area behind the cold front. [9] At this stage also it is expected that the "vortex signature" should appear as a spiral streakiness in the cloud pattern. This has been indicated by spiralling arrows in the schematic and can be readily seen in the TIROS photo. However, in many cases the contrast within the cloud pattern may be inadequate to permit seeing any pattern within the bright overcast area. These spiralling streaks suggest that by this stage there should be a significant trough, or even the beginning of a closed low, at 500 mb. In this stage, however, the cloud vortex is still more frequently related to a surface than a 500 mb center; and appears normally to be located slightly south and west of the related surface pressure center.

Another representative feature may be the cyclonic movement around the major cloud mass of the arching cloud bands formerly poleward of the low.

6.2.3.1 Synoptic-Scale Crescent-Shaped Cloud Patterns

Bright, overcast, crescent-shaped cloud patterns (such as that illustrated in Figure 6-8, with the crescent outlined in dashed black, slightly outside to permit the cloud edge to be seen), at times resembling in geometric outline this or the next stage, have been found to be associated with 500 mb trough patterns, not with closed 500 mb lows. In such cases, the clouds depict more the area of upward vertical velocity ahead of the trough rather than the streamlines of the air flow.

Corroboration of this interpretation has been provided by results of some recent, unpublished computations of vertical velocities by Prof. F. Sanders* of MIT, who has kindly lent these data to the authors. The computations evaluate

* These are an amplification of the studies reported in Reference 98.

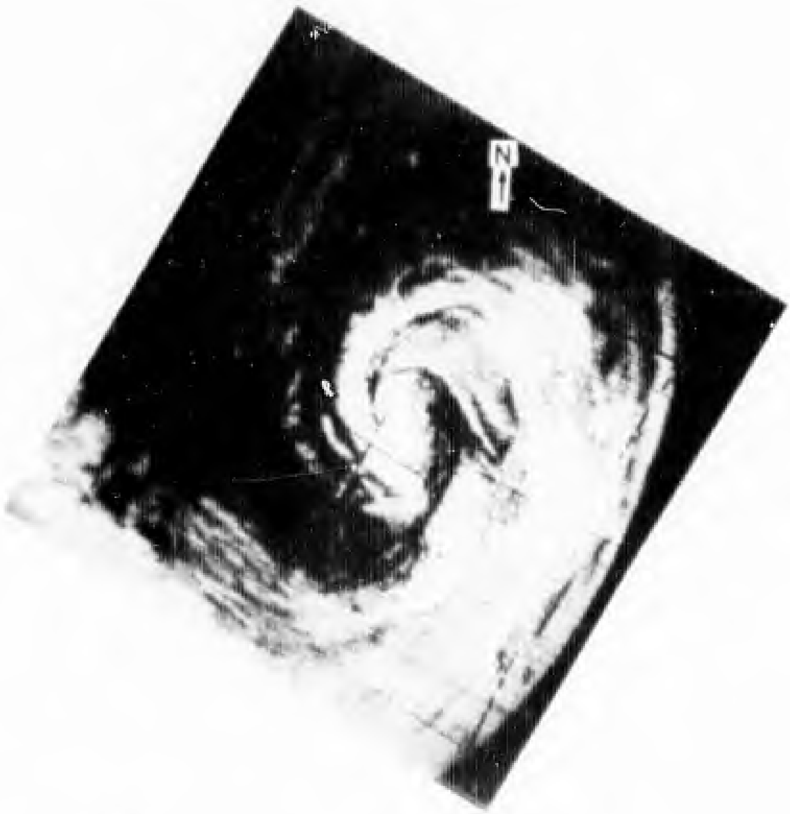


FIGURE LEGEND

— CLOUD

— LESS REFLECTIVE CLOUD

— LAND AND OCEAN

DOT—DASH LINE — TROUGHS AND RIDGES

DASHED LINES — LOWER TROPOSPHERE FLOW

DOUBLE SHAFT ARROW — DIRECTION OF SYSTEM MOVEMENT

HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW

SOLID LINE — MIDDLE TROPOSPHERE FLOW

Fig. 6-7 Beginning of Occlusion

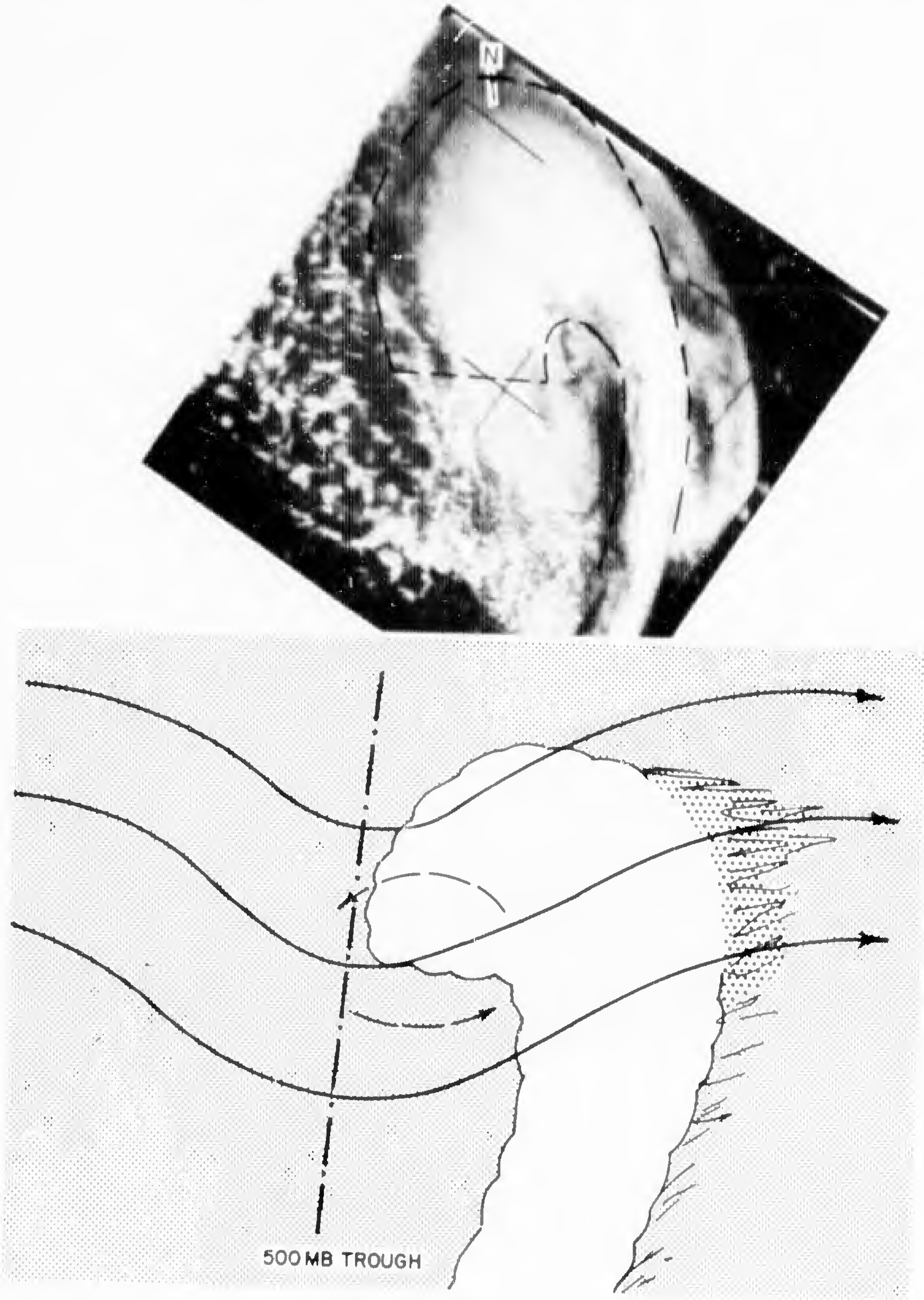


FIGURE LEGEND

— CLOUD

— LESS REFLECTIVE CLOUD

— LAND AND OCEAN

DOT—DASH LINE — TROUGHS AND RIDGES

DASHED LINES — LOWER TROPOSPHERE FLOW

DOUBLE SHAFT ARROW — DIRECTION OF SYSTEM MOVEMENT

HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW

SOLID LINE — MIDDLE TROPOSPHERE FLOW

Fig. 6-8 Example of Synoptic Scale Crescent Shaped Cloud Patterns Associated with 500-mb Troughs

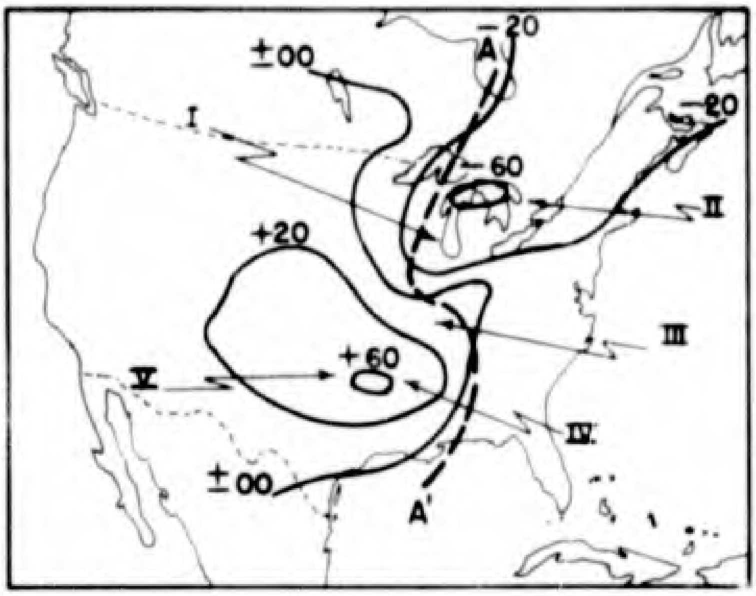


Fig. 6-9 Vertical Average (900-400 mb) of Vertical Velocity Field, 00Z, 22 January 1959. Units 10^{-4} mb/sec. Line A-A', Approximate Boundary of Middle and High Clouds.

separately the vertical velocity, ω_v, associated with the vorticity advection, and ω_t, the vertical velocity associated with the thermal advection (see Section 6.1.2).

The vertical velocities were computed for levels at 100-mb intervals from 1000-100 mb. The horizontal positions of vertical motion isopleths were then vertically averaged for the levels 900-400 mb. Representative positions of the maximum values of vertical velocity were also determined. The results of this analysis are presented in Figure 6-9.

The synoptic situation for which these computations were made[98] was that of 0000Z, 22 January 1959, which consisted of a trough at 500-mb and a deepening baroclinic low at the surface over the central United States. Obviously, this situation was not photographed by TIROS. One may ask if the cloud pattern associated with this system is similar to that seen in TIROS pictures. Analysis of conventional cloud observations and radiosonde data indicate the southern and western edge of the middle and high cloud deck is along the line A-A' in Figure 6-9. The shape of this line is very similar to the southern and western part of the crescent-shaped pattern in the TIROS picture in Figure 6-8.

Comparison of Figure 6-8 and Figure 6-9 shows that the shape of the $\pm$ 00 "total" vertical velocity isopleth is also very similar to the shape of the cloud edge in the western and southern portion of the crescent-shaped pattern in Figure 6-8. Upward vertical velocity is located north and east, and downward vertical velocity is located south and west, of this line.* The western part of the upward vertical velocity area, Region I, is dominated by maximum values of ω_v from 800-400 mb, while further east in Region II it is dominated by maximum values of ω_t. The easternmost part of the net downward vertical velocity area, Region III, is characterized by downward vertical motion from ω_t (900 - 700 mb) more than compensating for upward vertical velocity from ω_v (900 - 700 mb). In Region IV downward vertical velocity from ω_t (800 - 400 mb) predominates, while in Region V downward vertical velocity from ω_v (800 -400 mb) predominates.

A cloud analysis showed that the southwestern part of the cloud mass in Region I was essentially solid from the ground up to 400 - 300 mb, so that the cloud pattern that the satellite would see would be composed of cloud tops located at about these altitudes. The winds at these levels were southwest, not northeast. Further east in Region I there were northeast winds in the surface to 850 mb layer, but the cloud tops in this area were also around 300 mb. The fact that the low-level wind

* Since ω is computed and expressed in units of mb/sec, negative ω corresponds to upward vertical velocity, and vice versa.

direction lines up with the major axis of the upper-level cloud pattern should be taken as a coincidence between the atmospheric cloud and wind patterns at these different levels, rather than as necessarily having any physical significance regarding these two atmospheric parameters. Thus, in this case the comma-shaped cloud pattern indicated the distribution of the upward vertical velocity pattern; not the streamlines of air flow at the level of the cloud tops.

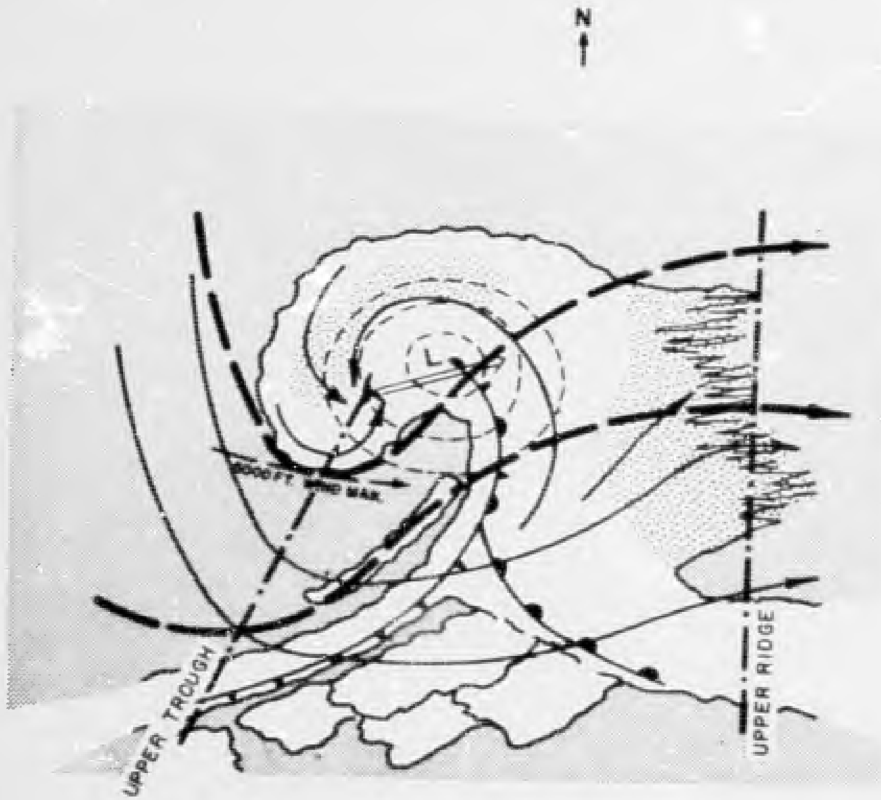
This comma-shaped pattern can often be identified by the abrupt termination of the crescent cloud pattern equatorward of a line west of the apparent circulation center (just north of the straight portion of the dash black outline in Fig. 6-8), with only scattered to broken lower level cloudiness in the quadrant west and equatorward of the apparent center. As illustrated in Figure 6-8, these crescent-shaped, bright overcasts are often accompanied by lower, frequently cumuliform, U-shaped or closed cloud patterns which appear to identify a surface pressure center.

6.2.4 Occluding Cyclone Stage

By this and subsequent stages, the cloud patterns are conspicuous, distinctive, and frequently observed. The key feature is the very definite intrusion of "clear" dry air eastward into the cloud mass behind the cold and occluded fronts, and the curvature of this dry and often cold air poleward around the center of the associated low. This stage is indicative of a significant circulation and is probably not typical of storms with only weak middle or upper level circulations.[9] In fact, a closed low extending to 500 mb, and perhaps throughout the troposphere, would normally be expected. Vortex patterns at this stage usually have related pressure centers, at both the surface and 500 mb, within 200 nautical miles of the vortex center.

The degree to which the dry air is essentially completely clear (Fig. 6-10) as compared to being partially filled with convective cloudiness (Fig. 6-11) seems to be a function of the humidity and stability of the cold air and of the surface under it.

The lowest central pressure at the surface frequently appears to occur with a degree of dry air intrusion only slightly greater than that in the schematic in Figure 6-10.[64] Vortices at this stage appear to have the greatest average departure (about 18 mb) from the normal seasonal surface pressure for their location.



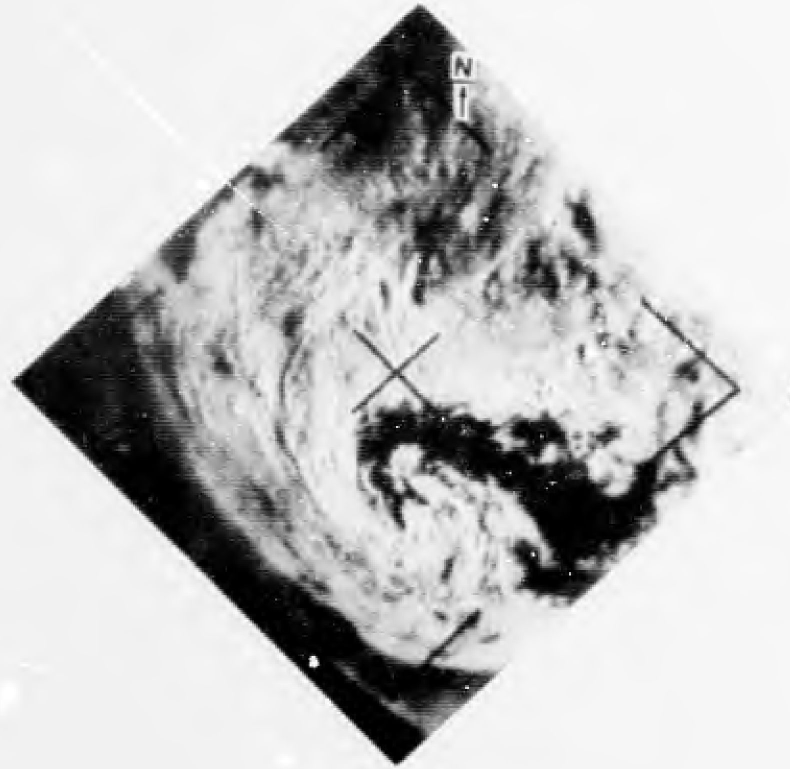


FIGURE LEGEND

— CLOUD

— LESS REFLECTIVE CLOUD

— LAND AND OCEAN

DOT–DASH LINE — TROUGHS AND RIDGES

DASHED LINES — LOWER TROPOSPHERE FLOW

DOUBLE SHAFT ARROW — DIRECTION OF SYSTEM MOVEMENT

HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW

SOLID LINE — MIDDLE TROPOSPHERE FLOW

Fig. 6-10 Occluding Cyclone

FIGURE LEGEND

— CLOUD

— LESS REFLECTIVE CLOUD

— LAND AND OCEAN

DOT—DASH LINE — TROUGHS AND RIDGES

DASHED LINES — LOWER TROPOSPHERE FLOW

DOUBLE SHAFT ARROW — DIRECTION OF SYSTEM MOVEMENT

HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW

SOLID LINE — MIDDLE TROPOSPHERE FLOW

Fig. 6-11 Occluding Cyclone, Convective Clouds in Cold Air

The corresponding average 500 mb departure is about 150 meters.*

Since the length and breadth of cloud streets is positively correlated with convergence, increased convective cloudiness in the cold dry air in this and the next stage may be indicative of deepening of the low.[102]

6.2.5 Fully Occluded, Mature Stage

In this stage, there may be virtue in considering two substages. In the first, prior to fullest maturity, the dry air continues to spiral in about the vortex, reaching a stage of one or more complete revolutions about the center (Fig. 6-12). In the second, the warmer moist air at upper levels first connects across the cold air aloft, cutting that inside off from any further supply, and the beginnings of dissipation are at hand (Fig. 6-13).

Accordingly, the degree of maturity is broadly shown by the increasing concentricity of the spiral bands and by a decreasing width of the clear air channel between them.[92] The length of time provided for development, prior to the closing off of the dry air aloft, may be indicative of the depth achieved at the center of the upper air low.[64] These mature vortices have average departures from the seasonal and geographic normal of about 16 mb at the surface, and about 180 meters at 500 mb. The average 500 mb departure at this stage appears to be the greatest observed.

The authors are not aware of any multi-level vertical velocity computations having, as yet, been carried out for a closed circulation in the middle troposphere, say 500 mb, which could be usefully related to cloud patterns at that stage of storm development.** However, physical reasoning based on the dynamical relationships between vertical velocity and vorticity and thermal advection (Section 6.1.2) provides a qualitative explanation of the basic pattern of middle and high clouds observed by TIROS to be associated with these closed circulations. This basic cloud pattern is characterized by long, clear and often spiral streaks in the middle

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* In the samples of data studied,[8] for this and the following two stages, the standard deviation of the 500 mb departure was about 50% of the observed average departure; the standard deviation of the surface pressure departure varied between 60% and 100% of the average departure. One would expect about two-thirds of the cases to fall between ± one standard deviation of the average. The available samples ranged between 7 and 25 cases.

** The effect of cloud element translations and deformations on cloud patterns associated with a cyclonic storm has recently been investigated, however. (See Holl, M. M., J. R. Clark, and R. E. Nagle, 1964: A Test of the Diagnostic-Cycle Routine, Final Report, Contract No. Cwb-10561, Meteorology International, Inc.).

and high cloud deck with the clear streaks tending to line up along the mean wind direction in the cloud layer. Also the cloud field tends toward symmetry with respect to the cloud vortex center.

As a closed circulation develops in the middle and upper troposphere, the wind field comes into phase with the vorticity and temperature fields. As the vorticity and thermal advection become weak, so does the vertical velocity. Weak upward vertical velocities do not produce thick, overcast cloudy areas and, for reasons not fully understood but possibly including effects of deformation, long, clear streaks appear in the cloud deck. The in-phase situation of the wind field and vorticity and thermal fields eliminates any preferred azimuths of upward and downward vertical velocity with respect to the vortex center. As a consequence the vertical motion and the cloud patterns become symmetrical about the vortex center.

Particularly during this and the remaining final stages of the system, pattern changes are slow (Fig. 6-14). Broad-scale changes in clouds occur only through a major development in the synoptic situation. Patterns in cloud systems may be recognizable for as many as four days, particularly in middle latitudes, and so permit a low to be identified from one day to the next [44, 102] (see Chapter 10).

6.2.5.1 Secondary Vortices

At this stage secondary vortices have in several cases been noted to the west of the primary circulation. These cumuliform and cirriform vortex patterns in the polar air flow behind major cyclones appear to be indicative of a 500-mb short wave trough and a distinct surface trough. Examples are shown in Figures 6-15 and 5-12. They have been noted at least twenty-four hours prior to any indication in the synoptic data.[78] These disturbances often develop into systems producing weather and precipitation of considerable operational significance. Other cases of possibly similar mesoscale vortices have been observed near the edge of the Antarctic pack ice[70] (Fig. 6-16).

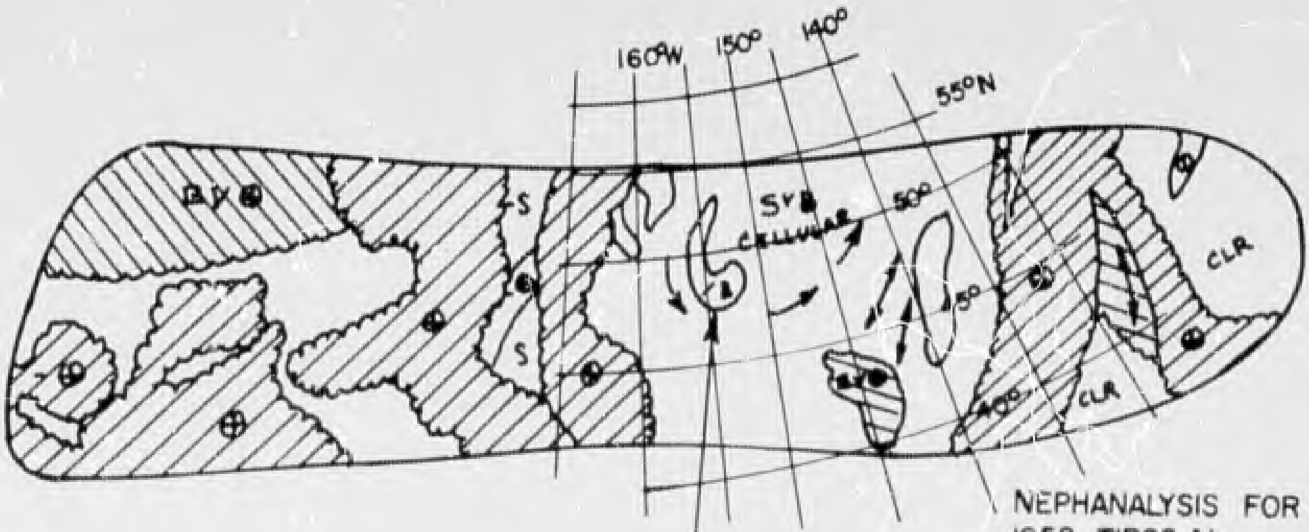
6.2.6 <u>The Dying Stage</u>

In this final stage, while organization is still apparent, there is some considerable variety to the configurations. The key factor seems to be the continued cut-off of the interior cold and dry air aloft by a surrounding ring of warmer, cloud-filled air (Fig. 6-17). This has been described as a ring cloud with an almost clear

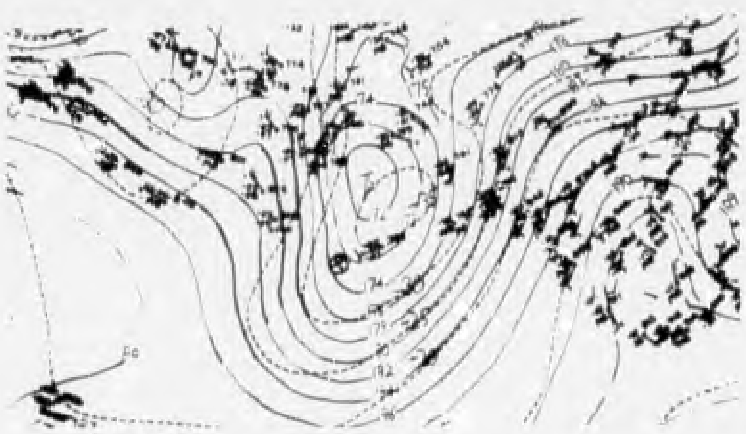
Fig. 6-14a 1624Z, 26 August 1962 - Vortex at 55N, 10.5W

Fig. 6-14b 1545Z, 27 August 1962 - Vortex at 56N, 7E

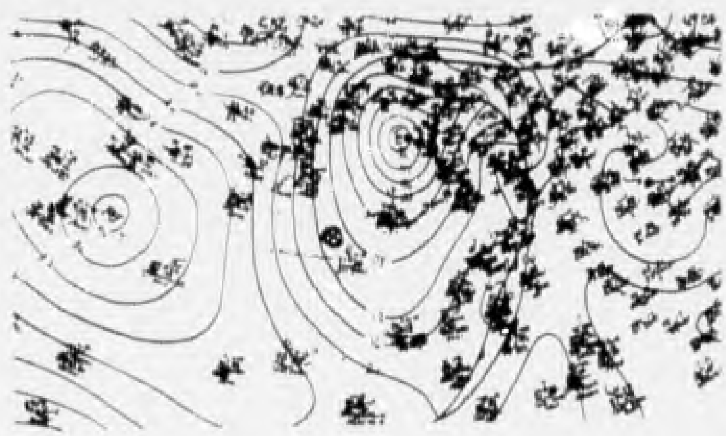
Fig. 6-14 Example of 24-hour Continuity in Cloud Patterns



NEPHANALYSIS FOR 1053RO
1052 TIROS IV
1940Z, 22 APRIL 1962



500MB CHART, 00Z, 23APRIL 1962



SURFACE CHART, 18Z, 22 APRIL 1962

⊗ INDICATES POSITION OF VORTEX FROM NEPH.

Fig. 6-15 Secondary Vortex in Polar Air Flow

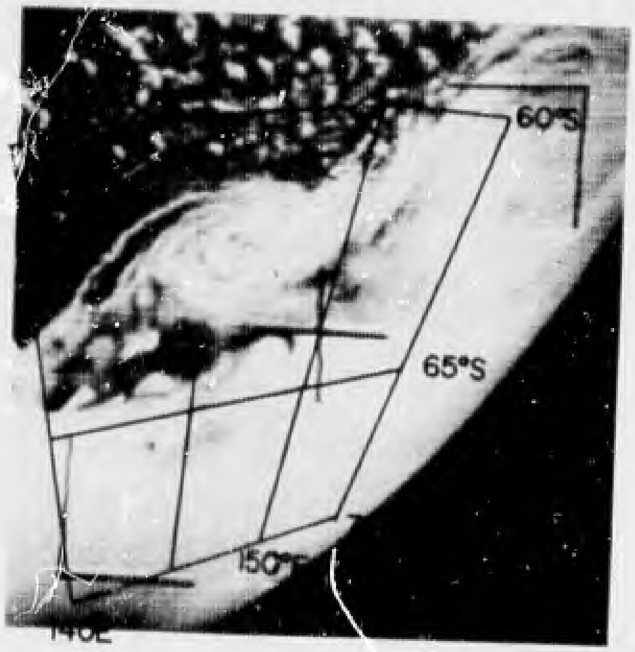


Fig. 6-16 Mesoscale Vortex off the Coast of Antarctica

center, corresponding to a cut-off cold low.[92] It is probable that the appearance is similar for both a major tropical vortex which has moved into temperate latitudes before decaying and a purely extratropical cold core system.

As the vortex decays, the number of cloud bands decreases, the space between bands increases, and the cloud cover at the crest or center of the vortex becomes more broken.[44,59] The number of cloud bands and their width, spacing, and character may vary with the underlying surface, season, and time of day as well as with circulation intensity.[9]

The clouds and their patterns often persist in the dying vortex after all indications in the synoptic data are lost.[9,61,102] It would thus appear that the clouds are a far more sensitive indicator of atmospheric activity than other types of data, detecting the earliest stages of cyclogenesis prior to other evidence (as discussed in relation to the Frontal Wave Stage) and showing the persistence of a low intensity circulation after it has otherwise become unapparent. For the analyst, this persistence indicates a need for caution to avoid forecasting more severe winds and weather than may actually be present in these final stages.

Cases have been noted where the intrusion of a band of moist, cloud-filled warmer air into the center of a cut-off cold core vortex (Fig. 6-17) may have been related to some degree of reintensification, or at least a temporary cessation of system degradation. While there is some evidence that major cloud systems may spiral into these now frontless storms, such cloud systems are much less well defined than in cyclones still directly associated with a front.

In cut-off cyclones, low-level vortices are usually characterized by a banded cumuliform appearance while those in the upper troposphere tend to be fibrous and stratiform[70] in appearance, as illustrated in Figures 6-17 and 6-18.

Dying Stage vortices have average departures from the seasonal and geographic normals of about 12 mb at the surface, and 120 meters at 500 mb.

6.3 VORTEX POSITION

6.3.1 Location Relative to Synoptic Data

The cloud vortex center tends to be west and/or equatorward of the surface low, following the track of the surface low but lagging behind its positions by about twelve hours.[9] It may be over the circulation center of the surface winds.[44] Coincidence of position between the cloud vortex and the 500 mb low seems to be

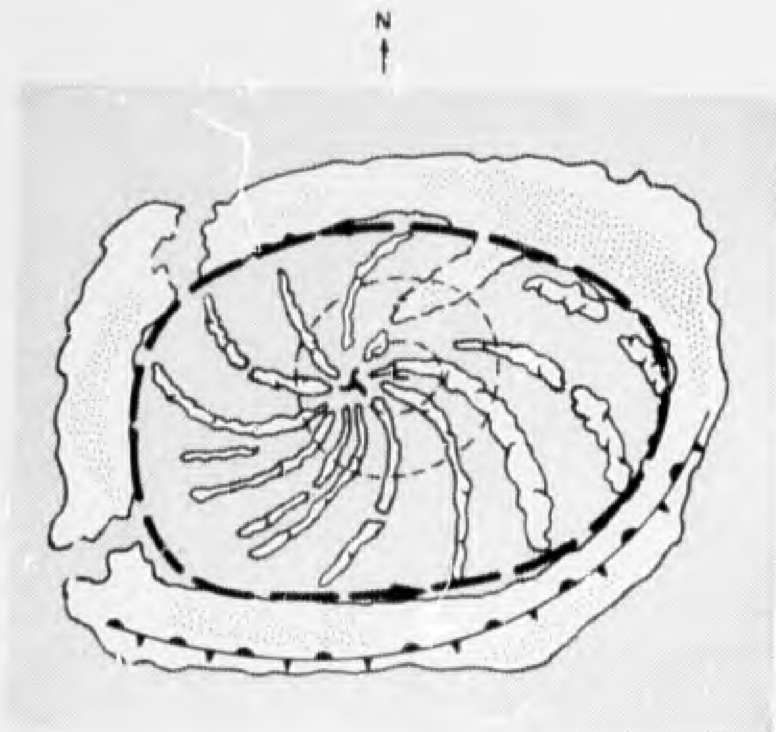


FIGURE LEGEND

— CLOUD

— LESS REFLECTIVE CLOUD

— LAND AND OCEAN

DASHED LINES — LOWER TROPOSPHERE FLOW
HEAVY DASHED LINES — TROPOPAUSE LEVEL FLOW

Fig. 6-17 Decaying Cyclone

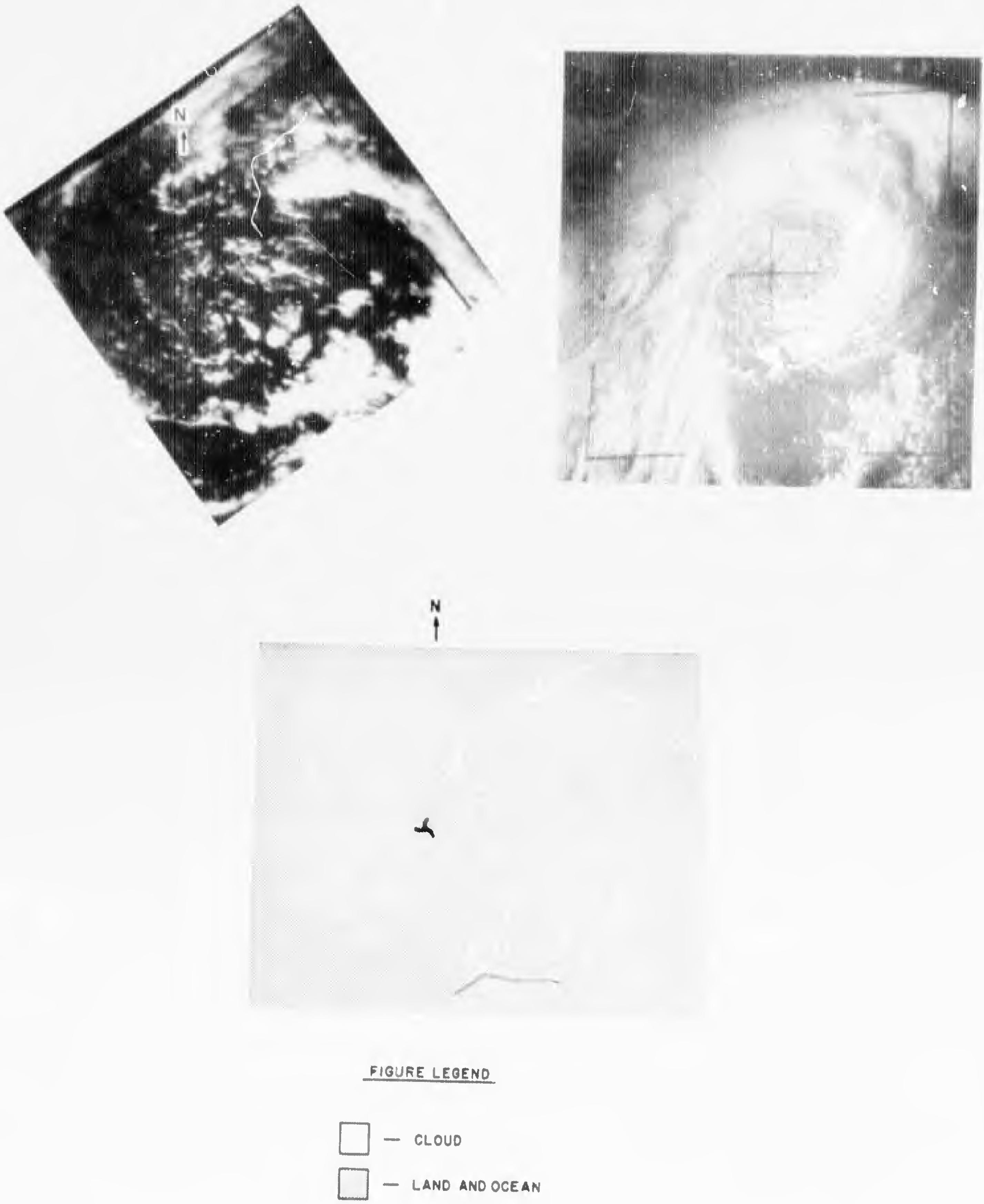


Fig. 6-18 Upper Level, Cut-off, Decaying Cyclone

somewhat better. In some cases, however, the cloud vortex center has been found to be west of the streamline vortex center at all levels from the surface to 500 mb.[55]

When two circulation centers are discernible during the cut-off stage, they may correspond to the pressure centers at different levels.[113]

The following relationships between vortex and pressure center positions have been frequently found to exist at specific stages of development:*

Beginning of Occlusion Stage: More frequently related to a surface than to a 500 mb low, with the cloud vortex slightly west and equatorward of the surface low.

Occluding Cyclone Stage: Nearly always within 200 miles of a surface low, and usually also within 200 miles of a 500 mb low. While the surface low positions tend to scatter about the cloud vortex, the 500 mb lows are usually located north or east of a northwest-southeast line passing through the position of the cloud vortex.

Fully Occluded Cyclone: The cloud vortex is usually within 200 miles of both a surface and a 500 mb low. The surface low has some tendency to be northeast of the cloud vortex, with the 500 mb low slightly displaced to the south of the surface low position.

Dying Cyclone: The related surface and 500 mb lows are usually found to the east of a north-south line through the cloud vortex center.

As shown in Figure 6-19, the one standard deviation circle for the differences between the positions of cloud vortices and related surface pressure centers appears to have a radius of about 148 nautical miles. For related 500 mb centers, the radius of the corresponding deviation circle is about 109 nautical miles. Inadequate conventional data and consequent inaccurate standard analyses may have been significant contributors to the magnitude of these values, so that the true representative values of the differences of positions between cloud vortices and related pressure centers are probably much less. It seems highly likely that when only cloud vortices related to pressure centers are considered (i. e., when those related only to troughs, or to other conventional synoptic features other than closed cyclones, are identified as discussed in Sections 6. 2. 3. 1 and 6. 2. 5. 1 and eliminated), the geographical locations of the cloud vortex and the pressure centers are only short distances apart.

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* The cases included in this study[8] were restricted to those situations in which the vortex appeared to be related to a closed circulation at either the surface or 500 mb.

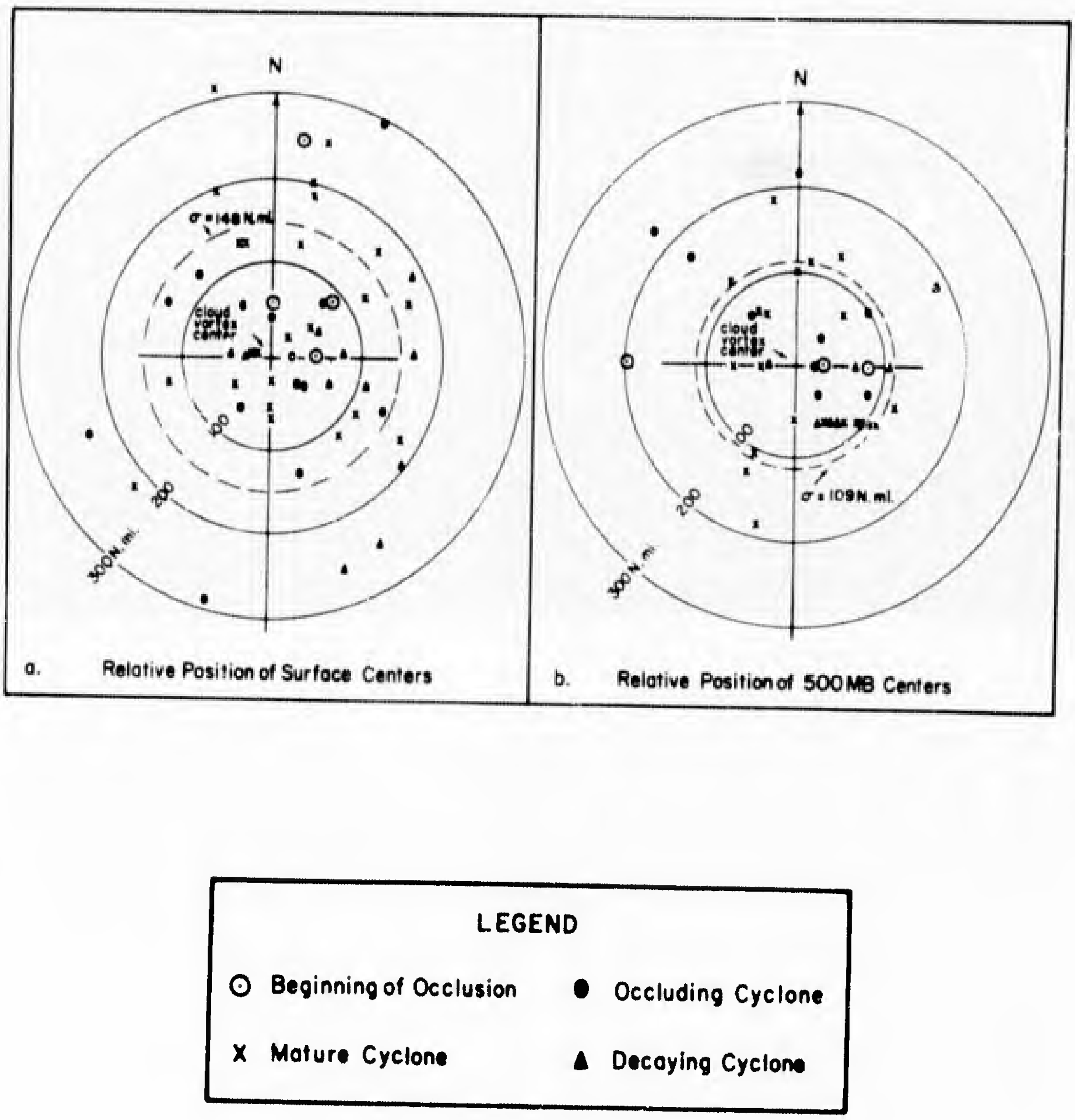

Fig. 6-19 Vortex Position Statistics.

Since a clearly defined cloud vortex seems to require the existence of an upper air circulation, the better correspondence observed between the cloud vortex and upper air pressure center (as compared to the surface center) seems reasonable in the more mature stages. In general, the more highly organized the vortex cloud patterns, the greater the tendency for them to be associated with more nearly vertical circulation systems and/or strong closed circulations in the middle troposphere.[12]

6. 3. 2 Altitude

As mentioned above, low level isolated vortices appear to be characterized by a banded cumuliform appearance while those in the upper troposphere tend to be banded stratiform. The relative cloud brightness gives some indication of the vertical extent of any vortex since brightness is usually positively correlated with the thickness of the clouds.[70]

6. 4 AIR MASSES IN THE VICINITY OF VORTICES

The satellite pictures of the cloud vortex patterns associated with cyclonic development often clearly depict the two air masses that are primarily involved:

1. The warm and typically moist tropical air which flows poleward ahead of the cold front. At least during the stages of active cyclonic development, the clouds in the pictures give the impression that this flow often seems to split just east of the center of circulation. One tongue of cloud appears to curve westward and eventually equatorward over and to the rear of the cyclone center. The other curves eastward and corresponds to the ascending warm air flow over the warm front (see Fig. 6-22, western most vortex). The role of vertical motion in forming these patterns, at least in the case of a short wave trough at 500 mb, was discussed in Section 6. 2. 3. 1. In the satellite pictures the area of warm air flow can be located by the convective cloudiness and instability lines ahead of the cold front (Fig. 7-1), and the major cloud bands and/or cloud mass located east and northeast of the vortex center, which are in part associated with the previously mentioned warm frontal cloud deck. These cloud patterns resemble, and so probably depict in part, the moist tongue configurations commonly noted in isentropic analysis.[11, 35, 44, 80]

2. The dry and typically colder air which moves into the storm from the west and poleward, curves equatorward of the circulation center, and spirals into it behind the cold front. This clear or clearer area (often it is substantially filled with cellular convective cloudiness) closely corresponds to an isentropic dry tongue.[44, 80]

In the mature and decaying cyclone, the cold dry air at upper levels is cut off, lying in the center of the storm surrounded by the warmer moist air (Fig. 6-17). In the lower troposphere, the tropical air mass would be expected to lie to the south of the large mature cyclone.

6.4.1 The Cold Dry Air

The degree of clearness or partial cloudiness in this air mass, sometimes referred to as the "clear" zone, is related to such parameters as humidity and the extent of subsidence, since the post-frontal cloud cover is governed by the thermal state of the cold air and the length of its trajectory.[9, 102] Dark clear areas are indicators of dry air when the presence of clouds would otherwise be expected.[11] This air mass has a tendency to be clear over land and more filled with convective clouds over the oceans.[64] The brighter clouds mark the areas of less stable air, as compared to those portions where the clouds appear greyer.[35] Post-frontal regions, in which fresh, cold air is involved, appear in satellite photographs as areas covered by small, cellular type clouds, often in streets but not necessarily so.[102] The mesoscale structure of these areas will be more fully discussed in Chapter 8. The "clear"area is indicative of and corresponds to subsiding dry air west of the trough,[92] and equatorward of a low level wind maximum which has been observed more or less along the equatorward edge of the cloud mass west of the vortex center.[111]

The orientations and shapes of these tongues of cold air to the rear of vortices, and especially those of their forward and side edges, are usually associated with the direction of the thermal wind in the lower troposphere as represented by the 1000-700 mb thickness isopleths. Thus, a system with an in-phase thermal field (approximately parallel to the middle troposphere contour field) may be indicated by a cold tongue spiraled around the central cloud body; a system characterized by an out-of-phase thickness field will tend to have a cold tongue penetrating more directly to the center of the cloud vortex, since a thickness (and horizontal temperature) gradient would then exist near the center of the cyclone.[12]

At the eastern boundary of the clear area, just behind the front, scattered cloud lines near the front may be clouds in the warm air above the front, with the last faint patches marking the leading edge of deep cold air. The equatorward and westerly sharp edges of the clouds around the vortex, west and equatorward of the center, may be the poleward and easterly edge of the subsiding air.[11] How well these boundaries can be seen will be dependent on the extent and location of convective cellular cloudiness in the dry air.

6.4.2 The Moist Warm Air

In many cases, the bright cloud areas corresponding to the warm moist air have insufficient contrast to depict any detail within this cloud mass, and uncertainty usually exists as to the altitude of the visible cloud tops. The processes associated with the cloud patterns for a short wave 500 mb trough were discussed in Section 6.2.3.1.

In the cases of a closed low in the middle troposphere, the cloud mass areas within the vortex, west and poleward of the clear area, may result in part from ascending motion of moist warmer air more or less along isentropic surfaces.[11,35] Accordingly, cloud top altitudes in these areas may in some cases decrease toward the pole. Penetration of the region of subsidence by clouds advected equatorward from the region of upward motion just poleward of the center is suggested by the pictures and seems plausible.[23]

6.4.3 Air Masses in the Mature and Decaying Cyclone

In the mature cyclone the stratiform clouds surrounding the storm mark a warm moist upper-level tongue which has encircled the storm center, which is now filled with cold, dry air. The stratiform cloud areas appear associated with upward motion. There may be upper level descending motion over the cumuliform cloud masses in the center.[35] (Fig. 6-17). In these stages the absence of cellular clouds in recirculated Arctic air can be taken as an indication of modification of such an air mass.[78]

As mentioned earlier, the clouds and cloud patterns may persist after all other synoptic indications of the decayed vortex appear to be lost.[102]

6.4.4 Humidity Near the Surface

In general, the surface relative humidity patterns appear well correlated with the distribution of low clouds, but in some regions vertical stability is sufficient to prevent low cloud formation in spite of adequate humidity.[111]

6.5 FRONTAL POSITIONS IN THE IMMEDIATE VICINITY OF A CLOUD VORTEX*

6.5.1 The Warm Front

There is usually little direct information on the position of the warm front relative to the vortex cloud patterns. By implication, it would be expected to be east of the vortex center. Seldom does there appear to be a clearly discernible boundary between the convective cloudiness in the warm air and the more stratiform cloudiness due to overrunning poleward of the surface warm sector. Accordingly, there seems presently to be little guidance for proper placement of the warm front within the cloudiness east of the vortex. Since, even with good synoptic observations, placement of the warm front is still often a problem, this ambiguity is not unexpected. The evidence shows that the classical concept of overrunning warm air is of secondary importance to the large scale lifting associated with the dynamics of the cyclone (see Section 6.1). Radar and detailed synoptic studies have substantiated this position and it would be surprising to find anything different from satellite information.

6.5.2 Cold and Occluded Fronts

6.5.2.1 Frontal Wave to Beginning of Occlusion Stages

During this phase, there is a tendency for the bulk of the frontal cloudiness to be west and poleward of the front (Figs. 6-4 through 6-6). East and equatorward of the front, conditions tend to be clear to broken convective cloudiness, but this warm sector convective cloudiness tends to become heavier east of the front as the vortex intensifies and one or more instability lines form. Such convective cloudiness will usually tend to have some breaks in it.[111]

* See Section 7.1.1 for a more general discussion of fronts.

When the cloud system lags behind the front, the upper winds are apt to be parallel to the front, at least as far as clouds extend.[102] This is compatible with wind flow-frontal orientation patterns to be anticipated during the early stages of development.

6.5.2.2 Occluded Stages

At these stages, the frontal band is generally much narrower, usually with comparatively definite breaking or clearing immediately to its rear (Figs. 6-12 and 6-13). Extensive cloudiness of a more or less broken convective nature is usually found to the east of the frontal band in the warm sector. At times, this convective area may take the form of a second band, east of and parallel to the frontal band, with a clear area or one of lesser cloudiness separating the frontal and convective bands (Fig. 7-1). The convective band is associated with a squall or instability line.

When the cloud mass lies ahead of the cold front with a sharp edge to the cloud system at the frontal boundary (rapid clearing), then the winds aloft are usually normal to the front. Such a frontal-winds-aloft configuration is more common in these occluded stages; the cloud mass is the convective cloudiness in the warm air ahead of the front, with a narrow and sharp frontal band behind.[102]

In the decaying stages of the cyclone (Fig. 5-14), with the frontal band less obvious, it may lie between the spiral bands to the west and an area of broken to overcast conditions to the east of the vortex, presumably the remains of the convective cloud-instability line area.[59] In these decaying vortices, the spiral bands west of the main frontal band or position (Fig. 5-23) may be the weather producers that have led to the frequent insertion in analyses of secondary cold fronts.[9]

The width of the frontal cloud band gives some indication of the steepness of the front, the western edge of the frontal band being about coincident with the 500 mb trough line.[9, 92] This, of course, suggests that the front becomes more vertical as the cyclone develops, which is to be expected as the 500 mb low moves over the surface low and the cold core cyclone itself becomes essentially vertical.

Experience has shown that when the frontal cloud band extending from an old or occluding vortex has a wider portion, lying generally east-west, equatorward of the vortex, and when this wider portion seems to be pinched or abruptly narrowed at its eastern end, development of a frontal wave is probable under this wider portion of the cloud band.[82] (See cloud pattern over Alabama in Figs. 10-1 and 10-2).

This widening and the associated wave development is most likely to coincide with the passage over the frontal band of a short wave trough, and its associated vorticity maxima, as they move around the major trough related to the existing vortex. Since the western end of the wider portion of the band usually lies near the 500 mb trough position, the mid-tropospheric winds are usually approximately parallel to the cloud band along this wider portion.

6.6 WINDS IN THE VICINITY OF VORTICES

The relationships between wind direction (let alone speed) and cloud patterns, lines, streets, bands, etc., are, at best, complex. Varied indications showing cloud orientations both parallel and perpendicular to the wind flow, as well as parallel to the wind shear vector, have been obtained in studies of satellite cloud pictures. It is probable that considerable time, study, and effort remain before completely unambiguous results are at hand. Some of these problems have already been briefly discussed in Section 2.2.3.1 (in relation to limits imposed by camera resolutions) and Chapter 4 (as related to cloud types and small scale cloud patterns). Further details will be discussed later in Chapter 8, and in Appendix C.

In spite of these problems and limitations, considerable information on the general nature of the wind field in the vicinity of vortices can usually be derived from the observed cloud patterns.

6.6.1 Low Level Winds

There are a number of suggestions for deducing low level winds from cloud patterns that are applicable in the vicinity of vortices. Streaky cloud patterns, presumably parallel to the wind flow, may indicate higher wind velocities than in the case of parallel lines of cellular clouds.[55] Cumulus cloud streets, generally parallel to the wind, are often found in the warm sector.[67] When the direction of the jet stream is known or can be deduced (see Section 6.6.2.2), cumulus cloud lines perpendicular to it may be indicative of strong low level shear.[102]

In storms just prior to the mature stage, the major cloud bands in the warm air (Fig. 7-1) tend to parallel the surface and 700 mb winds.[133] The "clear" air penetration into the cyclone may be due to a low level jet of dry air and, at about the occluding cyclone stage, a 5000 foot wind maximum has been observed to lie about along the equatorward edge of the cloud mass which has been advected equatorward west of the center of the low[111] (Figs. 6-10, 11, 12, 13).

The rate of circulation about the vortex can be deduced from the rate of advection of the dry air spiralling in from the west and the rate of penetration of the cloud cover moving over and west of the center from a more or less poleward direction.[64] It seems probable that the dry air speed is more representative of winds at intermediate levels, while the cloud mass movement applies more to upper level flows. During the occluding stage, changes in the width of the spiral clear area may indicate changes in the speed of circulation about the low since the spiral clear area in such cases is the result of an advection pattern made up in part by the movement of the low pressure area and also by a component of flow toward the center of the low. A decrease in either the speed of movement of the low or in the inflow component would result in a more circular advective pattern, especially in the southeast quadrant. A more circular advective pattern would in turn result in a decrease in the width of the spiral clear area. If no change in the speed of movement of a low can be detected at the surface and if it appears that no change in the speed of movement has occurred at any level in a system with a vertical slope, a decrease in width of the spiral clear area may be attributed to a decrease in circulation around the low.[64]

The wind/cloud-pattern relationships in the cold dry air behind extratropical cyclones have been the subject of particularly intensive investigation. At least a general indication of the wind direction is deducible from the fact that cellular cloud patterns in this portion of the storm occur with lower level cold air flow over a warmer water surface.[62, 130, 133]

The major, non-frontal bands of these cellular clouds (Fig. 5-23) may be perpendicular to the surface and the 700 mb flow.[130] Smaller cloud lines in the dry air under the inversion and cloud streets in post-frontal regions are apt to lie at an angle or even perpendicular to the wind flow in lower to middle levels.[64, 102]

In other cases, the clouds form into streets essentially parallel to the low level wind flow (Fig. 5-7). In some cases the lanes appear to follow the streamlines of the surface wind rather than the isobaric curvature. Cloud distributions of this latter nature may mean cross-isobar flow and considerable inflow into a low pressure center.[49]

Cloud streets in the interior of a mature cyclone (Fig. 6-17) generally parallel the wind, with some tendency to cross streamlines, converging towards the center.[35] This is probably due to little change in wind direction with height. In dissipating storms a fair to good correlation often exists between cloud bands equatorward and west of the storm center and the mean 1000-700 mb flow.[59]

At times an eroded area in the cloud field is noted behind the front (Fig. 6-20). It may coincide with a marked divergence of the isobars between the cyclonic flow around the surface low and the anticyclonic flow around the high to its rear.[49]

Other wind deductions from these cellular cloud patterns, at the mesoscale, will be discussed in Section 8.1.2.2.

6.6.2 Upper Level Winds

The clear association between the cloud vortex and the pressure center or minimum in the middle and upper troposphere of course implies wind relationships at these levels. Analogous relationships exist between the major trough and ridge positions, to be discussed in Section 6.8, and the middle and upper tropospheric wind flows in their vicinity.

In general, the large, dense cloud shields associated with vortices in the middle latitudes (Fig. 6-22) approximately parallel the predominant wind-flow in the lower and middle levels.[102] In the mature cyclone, a concentric band of high winds may exist between the outer warm air and the colder inner air according to the thermal wind relationship[35] (Fig. 6-17). Features in the cloud patterns along the edges of overcast areas may reveal mesoscale cyclonic and anticyclonic eddies.[35]

6.6.2.1 Major Cloud Pattern to the Rear and Poleward of the Vortex Center

On occasion, some vortex patterns seem to be inverted with little or no cloudiness in front (usually east) of the center but with the major spiral band extending toward the rear and poleward sides of the vortex. (An example is shown in Figure 10-18; note the vortex at 53N, 37W). It has been noted[82] that when this situation exists the contour pattern in the mid-troposphere has cyclonic curvature behind and poleward of the center and becomes anticyclonic just ahead of the trough line or just east of the center. The 500 mb contour field that can be inferred for cases such as this one is shown in Figure 10-18.

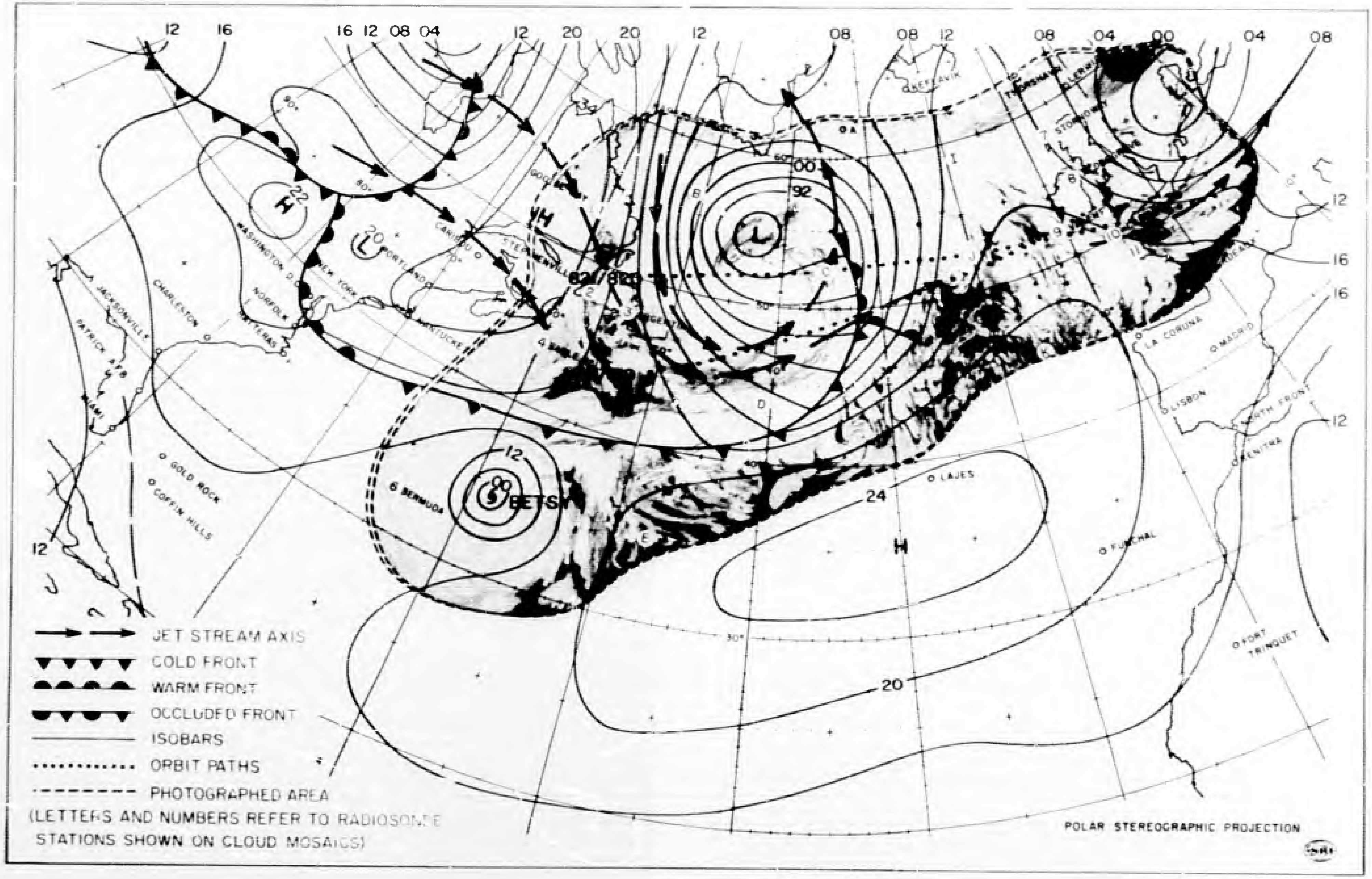

Fig. 6-20 Eroded Cloud Field Associated with Divergence of Surface Isobars, Area between 40-45N, 50-60W. (From Reference 49)

6.6.2.2 Jet Stream Relationships in the Vicinity of Vortices

With respect to the surface front, the jet stream is displaced poleward of the developing-wave stage of a cyclone. In later stages, as vortex development is initiated and progresses, the developing wave moves under the jet stream and, finally, in the occlusion stage, the jet stream centrum crosses the occlusion near, or slightly poleward of, the point of occlusion.[102] (Figs. 6-4, -5, -6, -7, -10, -11, -12, -13).

Accordingly the location of the jet stream relative to a vortex varies with the stages of the satellite-observed development pattern. The following configurations can be considered as typical:[70]

1. Open wave - 150-200 miles poleward of the broad bright area of the band. Thin bands may indicate the area (Figs. 6-4, 6-5). These thin bands, usually found 150-200 miles poleward of the major band, are often difficult to locate because of the lower cellular cloudiness. It is not yet obvious that the position of the jet stream can be determined outside of the area of the wave, although thin cirriform bands which relate to the jet stream can sometimes be observed (see also Section 7.1.3).

2. Pre-occlusion (and in the early stage of occlusion)-midway between the center of cloudiness about the vortex and the associated band. An isolated band of bright cloudiness may at times indicate this area (Figs. 6-6, -7).

3. Occlusion - Parallel to and just poleward of the major cloud band, from a point on the band equatorward and just west of the vortex center to just east of the center. A second band of maximum wind often is found starting somewhat west of the vortex. It blows along and parallel to the west and equatorward sides of the cloudiness surrounding the vortex center (Figs. 6-10, -11, -12, -13).

6.7 PRECIPITATION

An association between shower activity and brighter cloud areas or large bright cloud elements has been noted frequently in the satellite pictures.[9, 11, 35, 59, 111] However, only a low percentage of clouds are accompanied by precipitation.[78] A careful study of satellite cloud and radar precipitation data indicates that while, over a period of several hours, time integrated radar patterns often show reasonable correlation to the pattern of the brighter clouds, at any instant only a small portion of even a bright cloud may be precipitating.[77] Examples of bright clouds of

Light stippled area denotes continuous stratiform type precipitation; checked area, ragged patches of stratiform type precipitation; solid areas, convective type precipitation; x, pressure vortex center.

Fig. 6-21 Schematic Model of the Radar Precipitation Echo Distribution Around an Occluded Maritime Cyclone (From Reference 78) normally non-precipitating types, such as stratocumulus and thick stratus, are also frequent.[14] The failure to establish a relationship between brightness and precipitation may in part be due to premature saturation of the picture brightness scale, with inadequate contrast in the brighter areas. On the other hand, there are no good reasons why two cloud masses of similar thickness and composition, one precipitating and one not, should show any striking differences when viewed from above. As yet, no unique characteristics that distinguish precipitating from non-precipitating clouds have been determined. On a probability basis, however, a deep cloud mass (bright) is more likely to precipitate than a shallower, and consequently less bright, one.

Figure 6-21 shows a schematic diagram of the typical radar precipitation echo distribution around an occluded maritime cyclone; this distribution, which is not strikingly different from that in standard frontal cyclone models published in most meteorological texts, can provide guidance as to the more probable areas of precipitation in a satellite-observed cyclone.[78] The model shows the area of upslope precipitation, due to ascending motion associated with the cloudy area west and poleward of the storm center.[11]

Models such as this can be used for general guidance, but must be supplemented by an examination of the factors which contribute to the cloud and precipitation features in each section of a specific storm. Only then can the most probable actual conditions within a particular storm be determined.[61]

Heavy, persistent, and extensive precipitation has been observed in secondary outlying vortices (Fig. 5-12) formed in the cold air flow behind an occluded cyclone.[78] Periods of deteriorating weather may also be associated with the small scale vortices observed in the Antarctic[70] (Fig. 6-16).

6.8 VORTICES AND TROUGHS AS ANCHOR POINTS FOR THE ANALYSIS

It is obvious that those cloud patterns which are the most easily recognizable in the pictures should serve as anchor points for an analysis. Previous sections of this chapter have described in detail the shape, sizes, and position of cloud vortices relative to pressure and circulation centers established from conventional data. The relative positions of associated air masses, fronts, and upper and lower level streamline fields have also been discussed. When vortex patterns are coupled with available conventional data, the resulting synoptic analysis in their vicinity should usually provide a relatively accurate and detailed depiction of the current weather. In addition, other cloud patterns related to troughs and ridges can also aid in starting the analysis.

6.8.1 Relationships Between Cloud Vortices, The Classical Frontal Wave Model, And Surrounding Air Masses.

There is often an excellent correspondence between satellite-observed cloud patterns, other synoptic observations, and the classical frontal-wave model.[102] In such cases, the cloud distribution over a wide area can be associated with a schematic model of the relation of clouds, fronts, and jet streams within a wave system.[6] This cloud distribution is strongly supported by the TIROS mosaic[80,102] shown in Figure 6-22, when compared to the model of weather regions[6] shown in Figure 6-23. Essentially, this model contains eight weather regions related to the principal fronts and air masses. Descriptions of these weather regions can be found in many standard meteorological texts, such as Reference 86.

Other features that may be identified after the vortex or trough positions are located include:[102]

(1) Clouds in blocking anti-cyclones, which may have the fibrous, broken, and streaky appearance characteristic of middle and high clouds, with the orientation roughly parallel to the wind flow. The center of the ridge may be marked by an area of distinct clearing. (See Fig. 10-6 in the area near Greenland).

(2) The clouds associated with the high degree of moisture through a deep layer that is carried ahead of the cold fronts, with pronounced subsidence and drying within the front itself above about the 600 mb level. The post-frontal area is characterized by a moderate degree of moisture in a deep layer, coupled with low level instability. This translates into a satellite photograph of small cellular clouds. These distributions are perhaps typical of deep troughs with fronts and strong ridge conditions.[102] (Center of Fig. 6-22).

6.8.2 Trough and Ridge Positions as Identified by Satellite Cloud Patterns

The bulk of the frontal and vortex-associated cloudiness is usually found in and ahead of the 500 mb trough; and from general synoptic experience one expects the western edge of the frontal cloud band as seen in the satellite picture to typically lie along or somewhat ahead of the 500 mb trough line.[44,102,111] During situations of strong vortex development, when the axis of the upper trough is nearly over the

Fig. 6-22 TIROS Mosaic of Cyclone Family (From Reference 80)

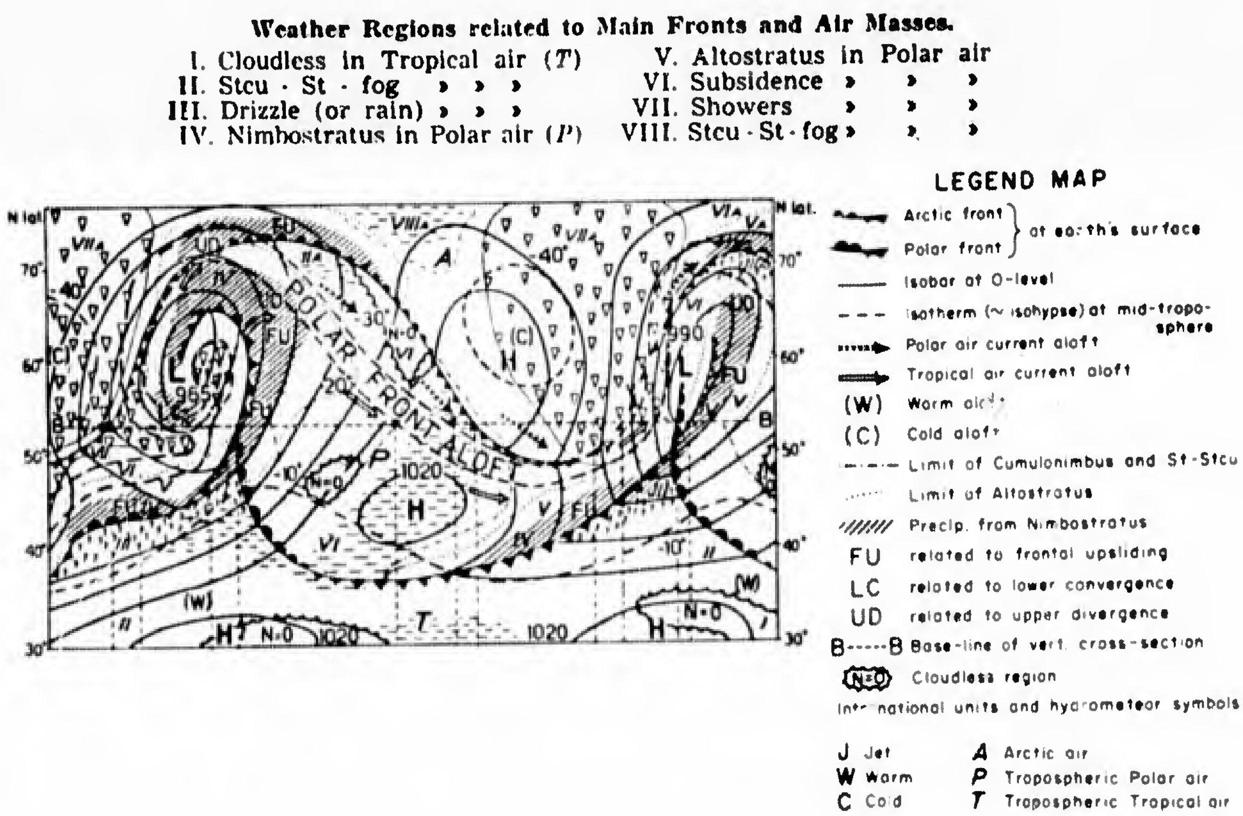

Fig. 6-23 Weather Regions Related to Main Fronts and Air Masses
(From Reference 102)

surface low-pressure center, the overrunning pre-frontal cloudiness, particularly the cirrus shield, will rarely proceed beyond the upper-level ridge line downstream.[102] Vortex development, with a spiraling in of the clear area, is promoted by strong meridional flow ahead of the low.[64]

It has also been found that:[70]

(a) The 300 mb trough is located over the east side of the cellular areas to the rear of major cyclones.

(b) The 300 mb ridge is located in or just to the east of the cloudiness associated with the surface low pressure system.

(c) The amplitude of the troughs and ridges at 300 mb is proportional to and indicated by the latitudinal extent of interrelated cloud patterns.

These trough-ridge relationships are illustrated in the schematics in Figures 6-5, 6-7, 6-10, 6-11, 6-12, 6-13, and in the nephanalyses discussed in Chapter 10.

Small-sized areas of cloud cover indicate troughs and ridges with short wave lengths and small amplitudes. Such small-sized areas are often triangular in shape, or comma- or crescent-shaped as discussed in Section 6. 2. 3. 1 and 6. 2.5. 1.

There are indications[81] that the character of the frontal cloud band leading out of the cloud vortex often changes at the place where it passes under the upper level trough line. East of the trough line, the frontal band tends to be rather solid and continuous, while at and to the west of the trough it often suddenly becomes distinctly broken in character (Fig. 5-24). Furthermore, when bands of significant size are formed just to the rear of the front by the spreading out and merging of the tops of stratocumulus or other moderate convective cloudiness, they often are found only to the west of the trough line. In such cases their eastern ends mark the upper trough line (Fig. 5-24). (These bands are further discussed in Section 7. 1. 1). This change in the character of the frontal band, and the termination of the post-frontal stratocumulus band, is logical when considered in terms of the probability of upward vertical motion being found ahead of the trough line, and subsidence to its rear.

6.8.2.1 Cloud Patterns Related To Ridge Amplitude

An indication of the ridge amplitude is given to some degree by the amount of cloud coverage, and by the cloud patterns under the ridge. In general, large-amplitude ridges are populated by sparse cloud cover near the center, and by long, striations or breaks in the cloud cover in the north, due to the large subsidence taking place in the ridge. Most of the time these long striations are meridionally oriented.[49] Examples of cloud conditions associated with ridges will be discussed and illustrated in Chapter 10,

CHAPTER 7

OTHER EXTRATROPICAL SYNOPTIC SCALE FEATURES

7.1 CLOUD BANDS

According to synoptic models, fronts are associated with bands or zones of cloudiness. In the classical examples, cold fronts are usually associated with relatively narrow bands of clouds; and warm fronts are associated with more extensive regions of cloudiness. While there have been a number of instances where "front-like" bands of clouds have existed where no front has appeared on conventional synoptic analyses, the forecaster is cautioned against minimizing their importance. The existence of these bands implies either the current or recent existence of organized upward motion. That this upward motion is ascribed to some process other than frontal lifting (see Section 6.1) does not diminish its practical importance.[50]

7.1.1 Fronts and Pre-Frontal Squall Lines

Many aspects of fronts have already been discussed in Section 6.5, especially those intimately related to vortices. These will not, in general, be reiterated here and the reader is referred to that section for additional discussions of tnese topics.

Broad and extensive frontal cloud bands (Fig. 5-3) have been found to be associated with pronounced large-amplitude troughs displaced well to the west of strong and elongated frontal zones, such that positive vorticity advection, upward motion, and upper air flow parallel to the front are present over a broad region east of the upper trough line.[12]

Quite frequently two parallel bright cloud bands are found along or parallel to the probable position of a front (Fig. 7-1); the eastern-most is more probably a line of convective activity under the moist tongue.[11] The surface position of the front is probably just under and along the eastern edge of the western cloud band, with the band of clouds to the west and the clearer (until the squall line convective cloudiness is reached) warm air to the east.[9, 11, 130, 133]

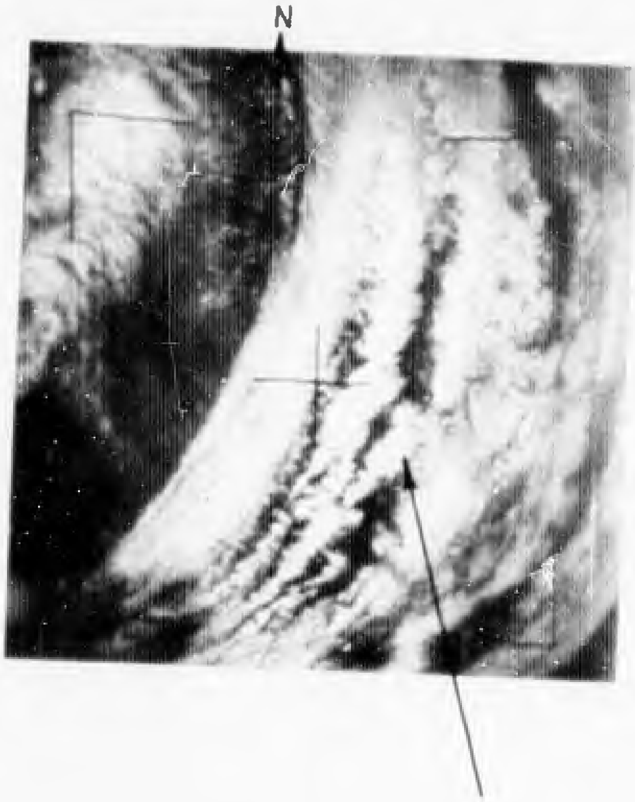

Fig. 7-1 Instability Line Cloud Band and Frontal Cloud Band

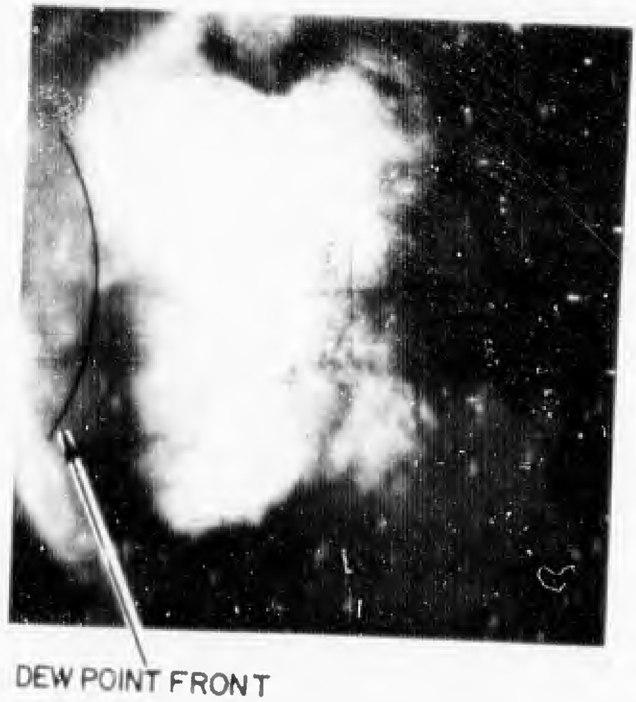

Fig. 7-2 Example of Cloud Pattern over Texas Area as Related to the Dew Point Front

Fig. 7-3 Example of Dew Point Front not Identifiable from Satellite Observed Cloud Pattern

Fig. 7-4 Cumuliform Cloud Mass Associated with Westward Surge of the Dew Point Front

The instability line ahead of the frontal band may often be differentiated from the front by the scalloped edges to the instability line clouds,[92, 113] as illustrated in Figures 7-1 and 5-22.

As discussed in Chapter 4 (see also Section 8. 1. 1), it appears that when very severe weather is associated with squall lines, the related clouds assume a distinctive and massive blob appearance (Figs. 4-10, 8-2). With few exceptions, there is then lacking the impression of the long line of cumulus development that might be expected. The line appearance of the convective, instability line area, as in Figures 5-22 and 7-1, seems to be more associated with either lack of severe weather, or early stages of squall line development prior to the outbreak of severe weather.[124]

Another type of cloud band that may parallel a cold front and create an ambiguous situation is found in the cold air behind the front. Under conditions of strong low level convection and an intense capping inversion, heavy cumulus and stratocumulus may form, spread out, and provide the appearance (Fig. 5-24) of a solid or nearly solid cloud band.[81] At times, these and other post-frontal bands (Fig. 5-23) may be associated with sufficient wind shifts and/or weather to cause the insertion of secondary cold fronts in conventional analyses.

Large variability has been observed in cloud and precipitation features both within a single storm or front, and between systems of apparently similar synoptic character.[61] This variability is only partially reduced by grouping systems with similar histories or similar stages of development. Accordingly, the classical models of weather in the vicinity of fronts and storms, including those presented in Chapter 6, appear to be as good as can be formulated on a general basis. The satellite data permit determination of the distribution of clouds in each specific case, from which some of the physical factors contributing to the distribution may be deduced. With such observations, the prediction of future cloud conditions should be significantly improved.

The remnants of a cold front can often be found in the satellite photographs even after it has moved well into the tropics (Fig. 5-21). Extensive cloud bands in the lower latitudes indicate that the effects of penetrations of cold air from the north are quite long-lasting — even after the means to detect fronts on the conventional basis have been lost (see also Section 11. 2. 1). On occasion, such bands can be followed westward to the frontal system lying to the west of the anti-cyclone.[102] The great influence of remnants of fronts and cyclones on the cloud field, long after they have become indistinct on the synoptic scale, has also been noted in temperate latitudes.[61]

The so-called Texas Dewpoint Front can sometimes be located from the satellite photographs, approximately along the boundary between the clear dry air to the west and the stratus cloud mass in the moist air to the east (Fig. 7-2). The match between the cloud patterns and the location of the front is not perfect, due partly to the thin layer of moist air (with only stratus of insufficient thickness to be seen in the satellite photographs) near the surface location of the dew-point front (Fig. 7-3). Occasionally, higher cloud layers, usually cirrus, partially mask the location of the dew-point front as pictured by the satellite. In a few cases, cloud patterns similar to those associated with the front appear in the pictures without a dewpoint front being present ;[52] again, the value of the integration of all available data is shown.

There appears to be a pronounced difference in the nature of the cloud cover when the dewpoint front is moving eastward and lowering (or collapsing), as compared to when there is a westward surge of the maritime air. The eastward motion appears to be associated with almost complete disappearance of the clouds while the westward surge seems to be accompanied by intensified cloud activity, including at times the cumuliform masses indicative of severe weather (Fig. 7-4).

7.1.2 Wind Relationships Near Fronts

When inference of the slope of a cold front is possible from the width of the frontal cloud band and/or the location of front relative to the associated cloudiness, consistency then suggests the most probable orientation of the upper air wind. Both katabatic* and anabatic** frontal cloud formations are observed, particularly with cold fronts. When the greater portion of the cloud mass lies ahead of the cold front with a sharp edge to the cloud system at the frontal boundary (rapid clearing), then the winds aloft are usually normal to the front (Fig. 7-1). When the cloud system lags behind the front (Figs. 6-4, -5), the upper winds are apt to be parallel to the front, at least as far as the clouds extend. Obviously, in an area of sparse data, the precise frontal location is difficult to determine, but if in the analysis one of these conditions is specified, then for reasons of consistency the direction of the

* Where the wind above the front blows with a component down the frontal slope, and so descends.

** Where the wind above the front blows with a component up the frontal slope, and so ascends.

upper wind flow appropriate to this condition should be chosen.

It has been found[82] that when there is a wide portion on a frontal cloud band equatorward of a vortex and lying generally east-west (as described in Section 6.5.2.2), the wider area of cloudiness approximately duplicates the area of higher speed westerlies in the mid-troposphere. That is, higher wind speeds are found within the area of the band, with lighter westerlies lying on either side (usually more or less north and south) of the band.

The occurrence of heavy cumuliform cloudiness in the immediate post-cold frontal region is quite common. Since this region is also one of great shear (i.e., through the frontal surface), in some cases, when cumuliform clouds penetrate into such a frontal zone, it should be possible to observe a shearing of the cloudiness above the frontal surface in the warm air (Fig. 7-5), and thereby the wind direction at that level. The orientation of the cloudiness is parallel to the wind at the shearing level.[70]

7.1.3 Jet Streams

Since the stages of vortex development are fairly well delineated in the cloud pictures, the location of the jet stream in the area of the vortices involving fronts is fairly readily established from front-jet-stream models (see Chapter 6). However, there are areas away from vortices where the jet stream is considerably displaced from the surface front and its associated cloudiness, and may lie over a totally different cloud field from that of a front. In this event the frontal cloud fields yield less exact clues to the location of the jet stream aloft. There is no direct duplication of the entire jet stream by a unique cloud configuration as seen from the satellite. The total cloud distribution over a wide area must be considered in jet stream analysis.[102] This is especially the case in jets which penetrate to low latitudes (equatorward of 30°).[70]

Certain observed relationships will aid in locating jet streams from satellite photographs. Some of these have been embodied in forecasting rules in the past. The more outstanding of these relationships are as follows:[102]

(1) The locations of jet streams can often be determined from cloud bands both in the vicinity of and away from fronts. Isolated banded cirrus associated with the jet stream will most often be found on the warm side of the jet, ahead of a trough and in an entrance area.[13] Single and multiple long, narrow, parallel bands

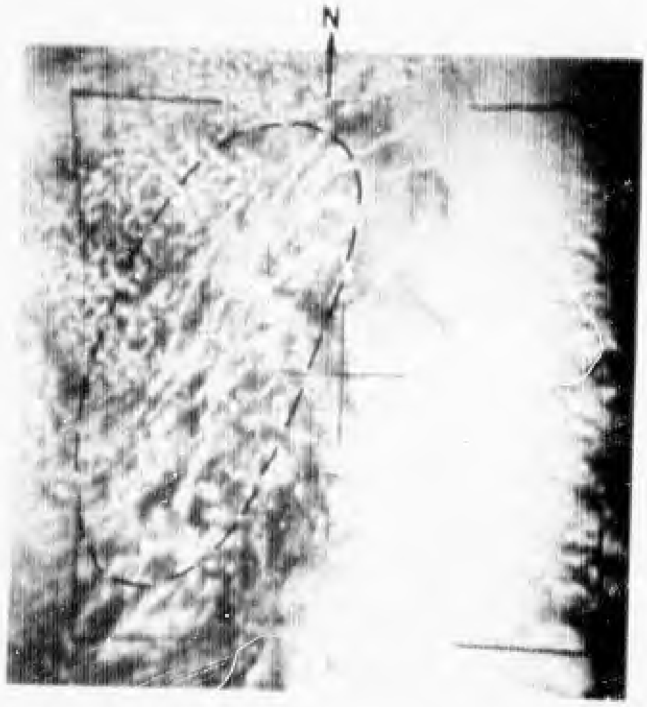

Fig. 7-5 Shearing of Cumuliform Clouds Extending through Frontal Zone

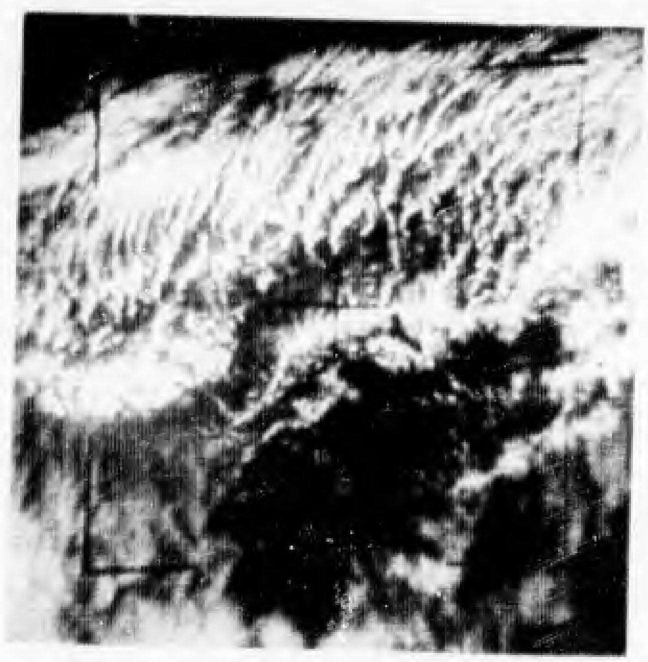

Fig. 7-6 Tropical Cloud Lines

of such cloudiness can often be seen in the satellite pictures (Fig. 4-14, 5-30) and related to jet streams just poleward of these bands (see also Section 4.2.2). This banding has been noted both well away from fronts, and also where the jet streams and the related cloud bands cross lower level cloudiness in the vicinity of vortices (Fig. 5-30). However, it must be kept in mind that many jet streams are not accompanied by such cloud bands (due to such causes as low humidities). Even when the bands are there, they may at times be too narrow to be detected in the satellite photographs, or have contrast inadequate to be detected against underlying and often extensive low level cloudiness.[53] At times such a band may become visible against the lower cloudiness by the shadow it casts,[81] as near the left side of Figure 4-14. Also, as discussed in Section 4.2.2, not all such cloud bands are parallel to jet streams.

(2) Frequently the jet stream lies nearly over the intersection of the polar frontal surface with the 500 mb level, and low level cloud masses may parallel the jet stream.[102] Depending on the frontal slope, the jet stream may be just or well poleward of the frontal cloud band. Where a cold frontal cloud band can be established as post frontal rather than pre-frontal, one can assume as a first approximation that the flow aloft is roughly parallel to the front and also that the jet stream is located near the cold side of the cloud band[50] (Figs. 6-4, -6). In these circumstances, the jet stream cloud bands and the poleward edge of the frontal cloud band are, at least in the satellite photographs, usually indistinguishable.[65] When a wave first forms on such a front (Fig. 6-4), it is not uncommon for the jet stream to continue along the poleward edge of the warm frontal cloud deck.[13] Jet stream positions during subsequent stages of development were discussed in Section 6.6.2.2 but, where the jet stream is normal to the cold front, direct association of cloud cover to jet-stream orientation is often not apparent.

(3) Jet streams on the east side of a long wave ridge are most apt to lie in clear air (Figs. 6-7, -10, -11, -12, -13). They are usually well organized, with strong horizontal and vertical shear through the front, and pronounced temperature gradients between air masses in the upper levels. These conditions will prevail along the jet stream to the area of the high-level cloud shield downstream, at which point the jet stream and its baroclinic zone usually diminish.

(4) When the isotach maximum passes over a high-pressure ridge the cloud system -- particularly the cirriform clouds -- will be elongated along this maximum and lie on the immediate warm side of the jet stream. Decay of these cloud systems usually occurs on the warm side of the jet stream exit region.

(5) The organized state of the jet stream will be weakest over the isentropic moist tongue to the east of a developing vortex, due to weakening of the temperature gradient in the upper levels. This is not to imply that strong winds will disappear, but rather that the horizontal and vertical shear will be lessened.

(6) As a rule, in a trough behind an occluding cyclone, the maximum-speed portion of the isotach field lies over clear air or over scattered to broken low-level cloud areas, depending upon the stage of cyclone development (Figs. 6-7, -10, -11, -12 -13). In this area the jet stream is often found to the east or equatorward of the major polygonal clusters of convective cloudiness[67] (Figs. 6-11, -12, -13).

7.2 MAJOR AREAS OF UNIFORM CHARACTERISTICS

Quite frequently, areas of quasi-synoptic size, covered with clouds of more or less homogeneous characteristics, will be noted in the satellite pictures. These are most common over oceans. Areas of cellular or cumuliform patterns, and of stratus, are often especially prominent.

7.2.1 Areas of Cellular*, Cumuliform Cloud Patterns

These mottled-appearing cloud areas (Figs. 4-11, 4-12, 5-6), characteristic of cumulus development in cold post-frontal air, often extend to rather low latitudes. In the area immediately poleward of the cold front where the depth of the cold air is shallow, the cloud elements may appear rather large, characteristic of clouds of limited vertical development (stratocumulus). Still further poleward of this zone, where the air is deeper, the clouds often present a smaller cell-like structure and are probably cumulus of greater vertical development. The center of a high pressure cell is generally free of clouds.[49]

These cellular appearing clouds are often arrayed in small circles or arcs surrounding hollow clear areas (Fig. 4-11). They exhibit something of the appearance of Bénard cells. The diameter of the circles range of the order of 20 to 50 miles. Synoptic data studies in a number of these situations show that

* These cellular cloud areas usually exhibit such small scale patterning as hollow polygonal cells, crescents, and/or vermiculated banding, as discussed in Sections 4.2.4 and 4.2.5.

these patterns appear in air masses which are slightly colder than the underlying water surfaces. The lapse rate is nearly adiabatic through the lower layer (some 3,000 to 10,000 feet deep). This unstable layer is usually capped by a well-marked inversion. Furthermore, the wind shear through the lower unstable layer is quite small. These patterns are more common over ocean areas than over land. It has been suggested for empirical as well as theoretical reasons that the larger the diameter of these circles, the deeper the layer of free convection, that is the higher the inversion. A rough initial estimate of the height of the inversion as being about 3% of the diameter of the circles formed by the cloud elements has been found.[50,62]

Under or immediately behind the cold front (Fig. 5-20, 7-1, 8-19), and especially also in areas further back than those of the cellular clouds where the inversion is somewhat higher, the cloud pattern is more likely to take the form of lines or streets.

Such cloud lines are particularly prevelant over tropical waters. The lines are apparently made up of cumulus and towering cumulus clouds (Fig. 7-6). It is probable that the clouds in different areas may extend to different altitudes. When this is true, the organization reflects the winds at different altitudes in different areas rather than resembling streamlines in a horizontal layer.[50]

7.2.2 Large Stratiform Areas

Large stratiform cloud areas are frequently found in the stable eastern areas of the oceanic sub-tropical anticyclones. They are a result of the cooling of air passing over cool water surfaces, but their persistence is enhanced by the low-level inversion which occurs as a result of large-scale descent and warming on the east side of these anticyclones. The inversion is itself reinforced by cooling from below. Typical areas are those off Northwest Africa (Fig. 5-5) and in the vicinity of the Canary and Madeira Islands, off Southwest Africa over the Benguela Current, off the west coast of California and Baja California over the California current (Fig. 4-16), and north of the Weddell Sea near the South Orkney and South Georgia Islands.[69,70]

These stratiform cloud areas appear to be considerably more streaky and patterned (Fig. 4-16) than might have been anticipated.[126] Often the patterns appear to be induced by disturbances in the flow in passing over island terrain (see Section 8. 2. 8) and to persist for some distance downstream from the islands (Fig. 5-18). A knowledge of local geography, combined with the observed patterns, may permit deductions as to the probable direction of flow at and just below the inversion level.[10, 56, 69]

MESOSCALE FEATURES

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CHAPTER 8

MESOSCALE FEATURES

The satellite data depict clearly the locations, sizes, extents, and shapes of mesoscale cloud features. This bridges the scales intermediate between features visible from a single surface observing station and those deducible from the combined data from several adjacent observing stations. Such precision of geographical location and extent, and geometrical shape, is seldom available from conventional data sources other than radar observations of precipitation.

Unfortunately, most of this mesoscale information is lost in the preparation of the facsimile transmitted nephanalyses. Because of this, cautions against assuming undue mesoscale precision in the nephs were presented in Section 2. 3. 3. When only the teletype nephs are available, only the largest mesoscale features can be expected to survive the coding process and even their locations may be expected to involve uncertainties of the order of 100 miles. Other cautions on the mesoscale use of the satellite data are discussed in Section 8. 5.

Mesoscale interpretation of the satellite data is greatly aided by their integration with available conventional observations, and vice versa. The conventional data, assisted by the limited cloud-type information the satellite can provide, may identify the nature of the weather process; the satellite data may then permit determination of the extent of the ground-observed conditions. At times, the combination may alter the overall interpretation, as in the case of apparently isolated thunderstorms (as seen from surface stations) being shown by the satellite pictures to be part of a major and essentially continuous line of convection[132] (Fig. 8-1).

Clouds and precipitation are greatly influenced by the mesoscale circulations and structures imbedded in synoptic patterns (such as fronts and cyclones), which may not be directly detectable from synoptic observations. A mesoscale cell or line structure can dominate the weather within a limited portion of one occluded cyclone, but have no counterpart in another and otherwise very similar cyclone. Circulations, either too young or too old and diffuse to be detected in a synoptic-scale analysis, can dominate the cloud and precipitation fields in their area. Cells and lines of clouds and precipitation may exist on the mesoscale and propagate somewhat independently of the synoptic scale motions.[61] The satellite can often provide information on these mesoscale patterns that would otherwise not be available to the analyst.

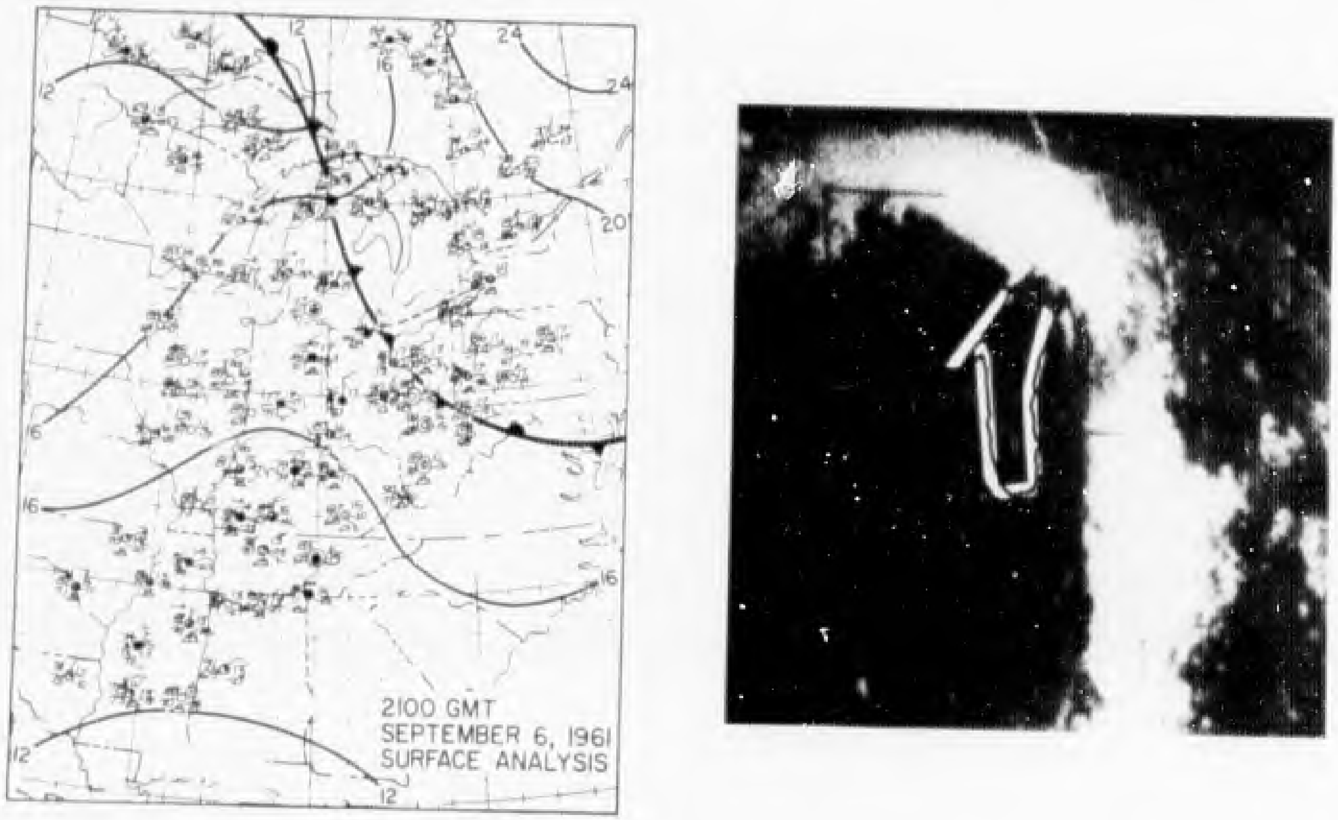

Fig. 8-1 TIROS View of a Squall Line, Extending from the Great Lakes Region Toward the Lower Mississippi Valley, when Conventional Data Suggested only Isolated Thunderstorms (From Reference 132)

8.1 CONVECTIVE CLOUDS AT THE MESOSCALE

Of the various scales of convective or cumuliform clouds, as seen from the satellite and discussed in Chapter 4, several provide mesoscale information.

8.1.1 Severe Storm Clouds

Perhaps most prominent are the bright, cumuliform cloud masses indicative of severe local weather. As discussed in Chapter 4, they are distinguished from other cumulus cloud patterns by the medium scale size and the unbroken, uniform appearance (Figs. 4-6, top left; 4-10, 8-2). They are usually either separated or completely isolated from other cloud cover (Fig. 4-10), and in the large-size range of the mesoscale spectrum, measuring between 100-200 miles in length. Being usually of a similar transverse dimension, they appear as massive cloud blobs. Although each pattern is seen as a large unit with little internal detail, the sharply defined borders, the scalloped appearance along portions of the border, and the overall intense brightness are indications of their convective nature.[124]

One of the most distinctive characteristics is the massive blob appearance of the storm clouds (Fig. 8-2). With few exceptions there have been no clear observations of a long line of cumulus development which might be expected in cases of squall lines. Though the cloud masses appear uniform and unbroken, radar and surface observations show that the masses are not uniform either in structure or in weather produced. The radar echoes are collectively much smaller than the host clouds. One would naturally expect instantaneous shower areas to be smaller than the convective cloud producing them. However, the concentrated nature of the radar echoes, and surface observations beneath severe local storms, indicate that while such storms are composed of many convective clouds in varying phases of development, they contain a concentrated area of vigorous convection. When viewing a mature storm system, the satellite does not see the many closely grouped cumulonimbus clouds in the convective area but rather the anvils which have united and expanded beyond the bounds of the storm area.

The exceptions to the mass appearance of the storm clouds have been lines of convective clouds in a very early stage of development (Fig. 8-3), and in these cases the observations preceded the outbreak of hail, wind and rainstorms by more than two hours. In the other cases, development had begun some time before that of the picture and the severe weather was either occurring or imminent. The forecaster

Fig. 8-2 Cumuliform Cloud Masses Associated with Severe Local Weather (Note also Cumulus Cloud Lines, Perpendicular to the Wind, in Lower Left)

Fig. 8-3 Lines of Convective Clouds which Later Produced Severe Local Weather

should be alert for signs of such incipient squall lines in satellite photographs; they may show themselves as lines of apparently developing cumulus clouds not yet having reached the thunderstorm stage and not yet within range of radar or surface weather reporting facilities.

An adjunct characteristic of the severe storm cloud pattern is the contiguous clear area (Figs. 4-6, 8-2). The size of the area varies within wide limits. Sometimes it appears as a hole in a large cloud layer around the storm cloud system, suggesting its formation is caused by subsidence compensating for the intense convection in the storm area (Fig. 4-10). Hence, the size of the adjacent clear area may be useful in determining the severity or potential severity of the storm system. At other times, the clear area is so vast, covering many thousands of square miles, that it must be independent of any intense local convection.

Evidence indicates the potential of tracking severe weather systems with satellites. Though this is seldom possible with the TIROS series, other satellites are anticipated which may eventually give more frequent or even continuous coverage of the earth.[124]

8.1.2 Convective Cloudiness of Lesser Severity

Smaller cumuliform clouds, whether in random arrays, polygonal clusters (Fig. 8-7), or cloud lines or streets (Fig. 4-22), may reveal the gradient of atmospheric stability over an area, or may indicate sub-areas of greater or lesser relative stability. More intensive cumulus activity, as revealed by greater concentrations of cumuliform clouds (Fig. 4-9), or individual cloud masses of larger size, is indicative of greater instability[100] (as, for example, over the heated surface of a tropical island in the afternoon, as compared to over the cooler adjacent ocean surface; see area over Cuba in Fig. 5-16, to left of center fiducial).

Distributions of low-level cumuliform clouds relative to a coast or the shore of a major lake can often be informative.[14, 50, 88] Since cumuliform clouds will tend to form over the warmer of the adjacent land-water surfaces, and to be suppressed over the cooler (Fig. 8-4), the clouds often extend across the boundary when the flow is from the warmer to the cooler surface. (Fig. 8-5a, note how clouds extend barely beyond New England coast line). When the flow is from the cooler to the warmer surface, the first clouds seen will be somewhat downwind from the shoreline (Fig. 8-5b). Examples of these conditions are often seen over the Great Lakes; during summer, daytime cumulus formation will be induced over the warm land and

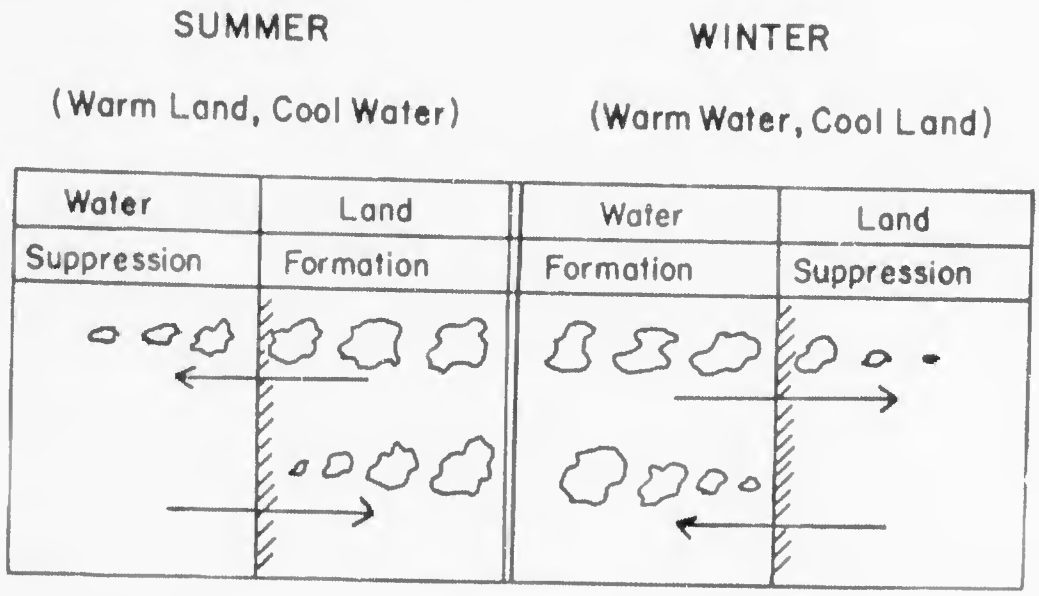

Fig. 8-4 Wind Direction Shown by Arrows in Relation to Cumulus Cloud Formation and Suppression over Adjacent Land and Water Areas (From Reference 14)

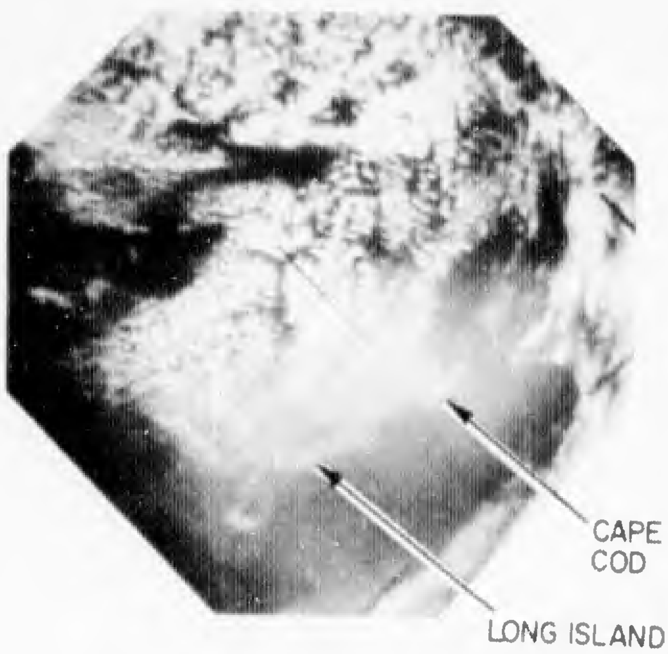

Fig. 8-5a Offshore Flow

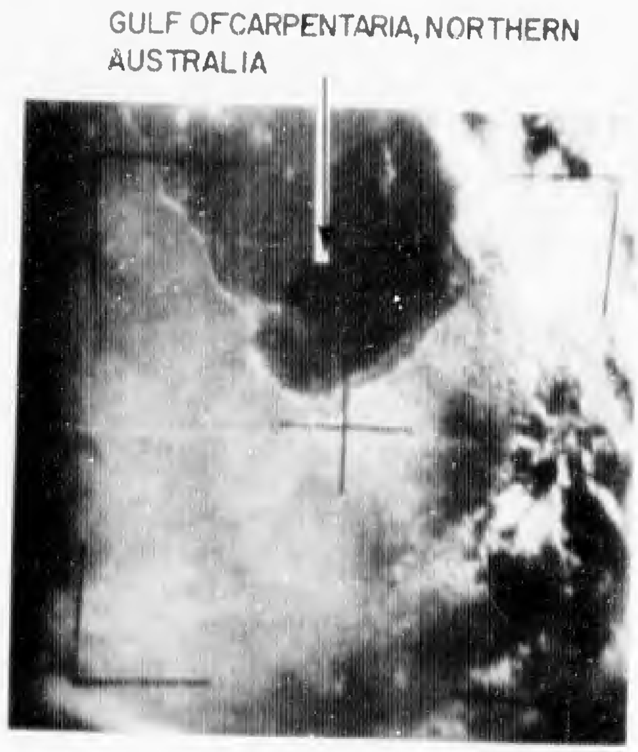

Fig. 8-5b Onshore Flow

Fig. 8-5 Distribution of Cloudiness Relative to Coastline During the Summer Season suppressed over the cooler lakes. In winter, at least prior to freeze-up, the reverse can be noted. Obviously, these conditions provide gross wind direction information.

Furthermore, since stratus and fog is induced by underlying cool surfaces, and cumulus by heating from below, cloudiness seen only over land, or water, and terminating approximately at a coast (Figs. 4-16, 5-5) can provide a clue to the cloud type where resolution is inadequate.[112]

Knowledge as to exact areas of cumuliform cloudiness over mountainous areas (Fig. 4-9), whose existence is often partially induced by upslope flows on a local scale since convection starts earlier and is more intense over mountain ranges (see Section 8.2), is often lacking due to the sparsity and/or wide spacing of observing stations.[112] Here, the satellite data can be particularly valuable.[50] Where the terrain is known and the cloud positions relative to it can be determined, wind direction information can often also be deduced (see Section 8.2). The problems of differentiating between clouds and snow covered mountains must, of course, be considered (see Section 9.4).

8.1.2.1 Cumuliform Cloud Lines and Streets

Parallel lines of cumulus, or cumuliform appearing cloud lines, of various widths, lengths, line spacings, and apparent cell sizes are frequently found among the mesoscale features seen in the satellite pictures (Figs. 4-5, 4-6, 4-13, 4-22, 7-6). In the simpler cases, these cloud lines might be expected to be either parallel to the wind (cloud streets) (Fig. 4-22) or perpendicular to the wind (billow clouds) (Fig. 4-5). Unfortunately, cloud line orientations as seen in the satellite pictures have been variously found to be not only parallel or perpendicular to the wind flow, but also parallel to the wind shear vector. More detailed discussions of some recent studies and findings on these matters (based principally on other than satellite data), and their physical basis, are given in Appendix C.

No effective keys to differentiating between cloud lines parallel, and those oriented perpendicular or at an angle to the wind have yet been found. Consequently, the use of cloud lines for wind determination should be approached conservatively in the absence of other data.

In a few situations, the overall synoptic pattern or even a single data point may be sufficient to resolve the cloud-wind orientation uncertainty. For example, if a smoothly curving cloud line field (Fig. 4-22) is known to be parallel to the wind along one part, continued parallelism and so a curvature of the wind flow is a reasonable deduction.

Cloud streets approximately parallel to the wind have been found in the trade wind areas of the tropics, associated with the low-level inflow into major tropical storms (Fig. 5-10), associated with various circulations about extratropical cyclones (Fig. 4-22), and in other situations. Unfortunately, in many similar situations, cloud lines not parallel to the wind have been observed.

Winds perpendicular to cloud line orientations have been observed in the warm air ahead of cold fronts over the central United States, often within a few hundred miles of heavy cumulus cloud masses associated with severe local storms.[123,125] The clouds seen in these cases appeared to be composed of conglomerates of cumulus cells of considerable vertical development (Figs. 4-6, 8-2). The theory of billow clouds[51] applies to clouds of small vertical development, and has been verified for such clouds. It is reasonable, however, to assume that the billow cloud waves, created on the inversion surface common in such situations, provided sufficient vertical motion to release latent instability and lead to the formation of towering cumulus. Furthermore, as these towering cumulus developed, some cloud rows would be accentuated at the cost of damping out others along intermediate wave lines, thus increasing the apparent wavelength between the cloud lines from that usual for billow clouds (the order of a very few miles) to wavelengths resolvable in the satellite pictures (the order of ten miles). Such suppression of intermediate cloud lines has been noted in other modes of line formation.[13]

8.1.2.2 Cellular Convective Clouds

The general nature and mode of formation of these cloud areas, and their synoptic scale significance, have already been discussed in Section 7.2.1. As mentioned there, the sizes of the individual cells within portions of these areas, and the small scale patterns into which they are arranged, may provide clues as to the relative low level stability and/or the height of the overlying inversion.

These areas are indicative of small vertical wind shear in the lower layers of the atmosphere.[92] The shear is mainly in wind speed, the direction remaining essentially constant with height. Thus it has been possible to derive useful relationships between specific small scale cloud patterns frequently seen in these areas and the low level wind.[70]

In order to relate cumuliform patterns to the low-level wind direction and speed, we need a cumuliform-producing layer which satisfies one of the two following conditions:

a. No vertical shear

b. Vertical shear parallel to the direction of the low-level wind.

The second condition is likely to be satisfied when the convective cloud layer is sufficiently shallow to make significant changes in wind direction improbable. The cumuliform patterns in the regions to the rear of major cyclones are often constrained to the first few thousand feet above the surface by a low-level subsidence inversion they cannot penetrate. The following wind velocity/cloud pattern categories have been tentatively devised for determining wind speed and direction in these areas (see Fig. 8-6):

A) <u>Wind Speed 0-12 knots - Polygonal or Elliptical Chains</u>

1) At the low end of this wind speed range, the cumuliform pattern is composed of regular, hollow, polygonal cells. These provide no information about the wind direction (Figs. 8-6 and 8-7).

2) Toward the higher end of the speed range, the polygonal cells are distorted into ellipses which tend to line up in a chainlike pattern. The wind direction is parallel to the major axis of the ellipse chain (Figs. 8-6 and 8-8).

B) <u>Wind Speed 13-22 knots - Scalloped (Vermiculated) and Highly Elliptical</u>

1) Vermiculated chain-like cloud patterns with the crosswind links missing (Figs. 8-6 and 8-9).

2) Highly elliptical or oblong patterns (Figs. 8-6 and 8-10).

In both of these cloud pattern types, the wind is parallel to the longer dimension of the elements or groups of cloud elements.

C) <u>Wind Speed 23-37 knots - "Blown-out" Ellipses and Rows*</u>

1) In the lower end of this wind speed range the pattern appears like "blown-out" ellipses which have an open end; the ellipses are no longer joined together in a chain. The wind is parallel to the major axis of the ellipse (Figs. 8-6 and 8-11).

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* For an interpretation of the term "Rows" as used here, see the schematic in Fig. 8-6.

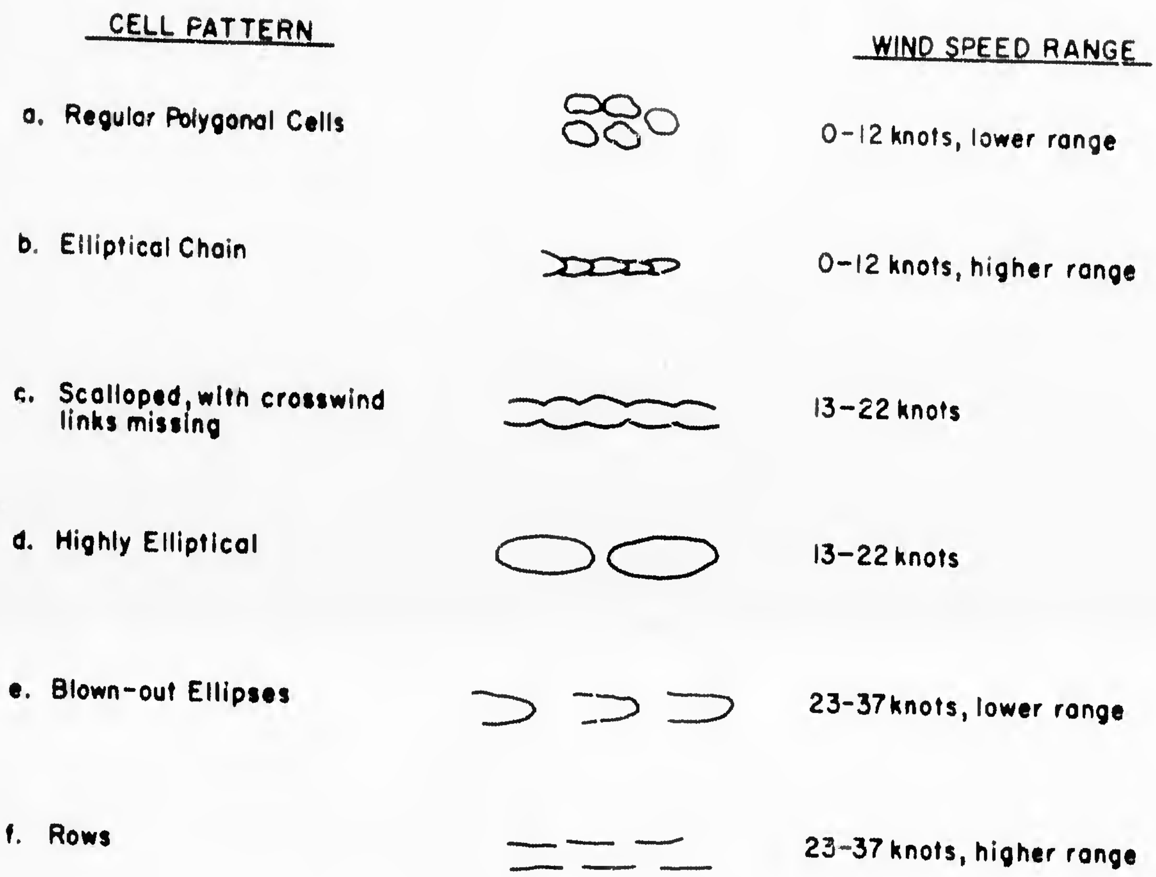

Fig. 8-6 Relationships Between Cumuliform Cell Patterns and Wind Velocity Categories in Regions to the Rear of Major Cyclones

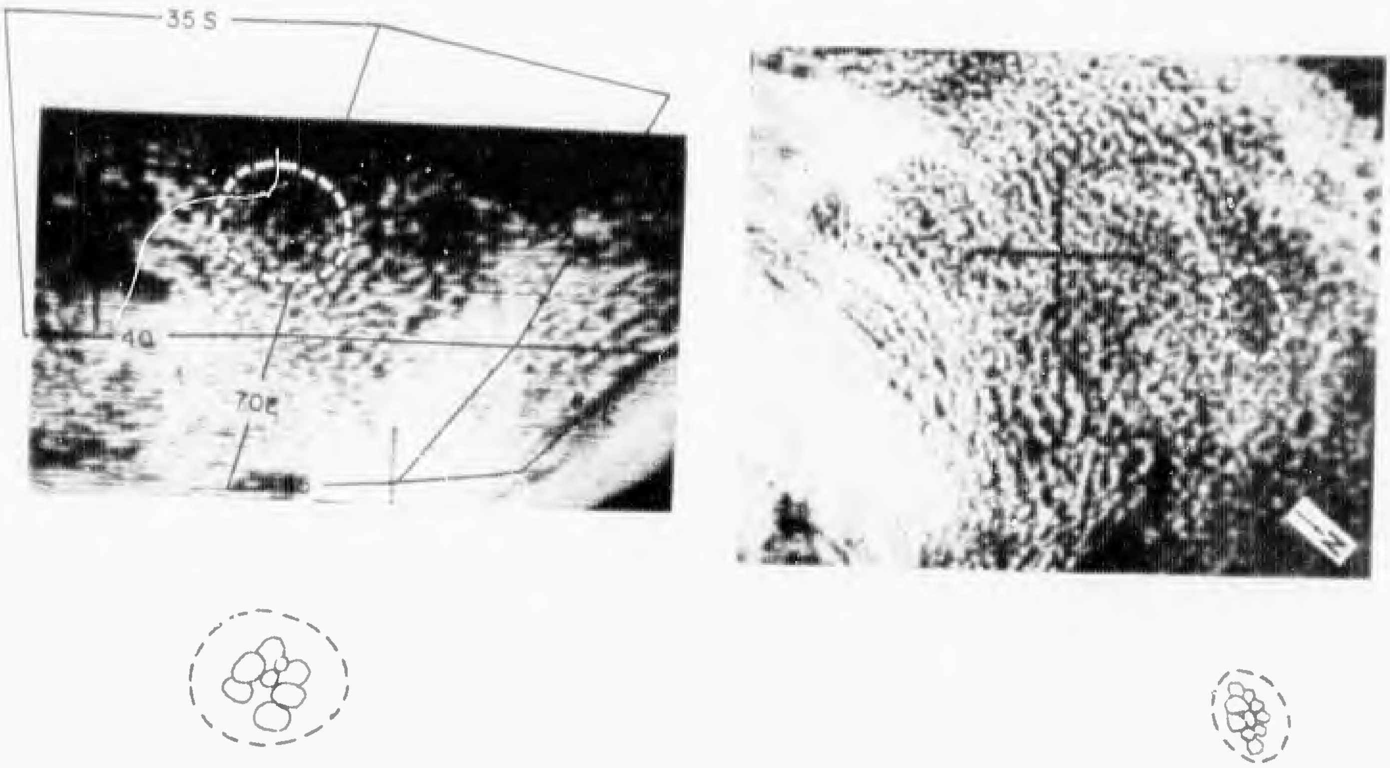

Fig. 8-7 Regular Polygonal Cells

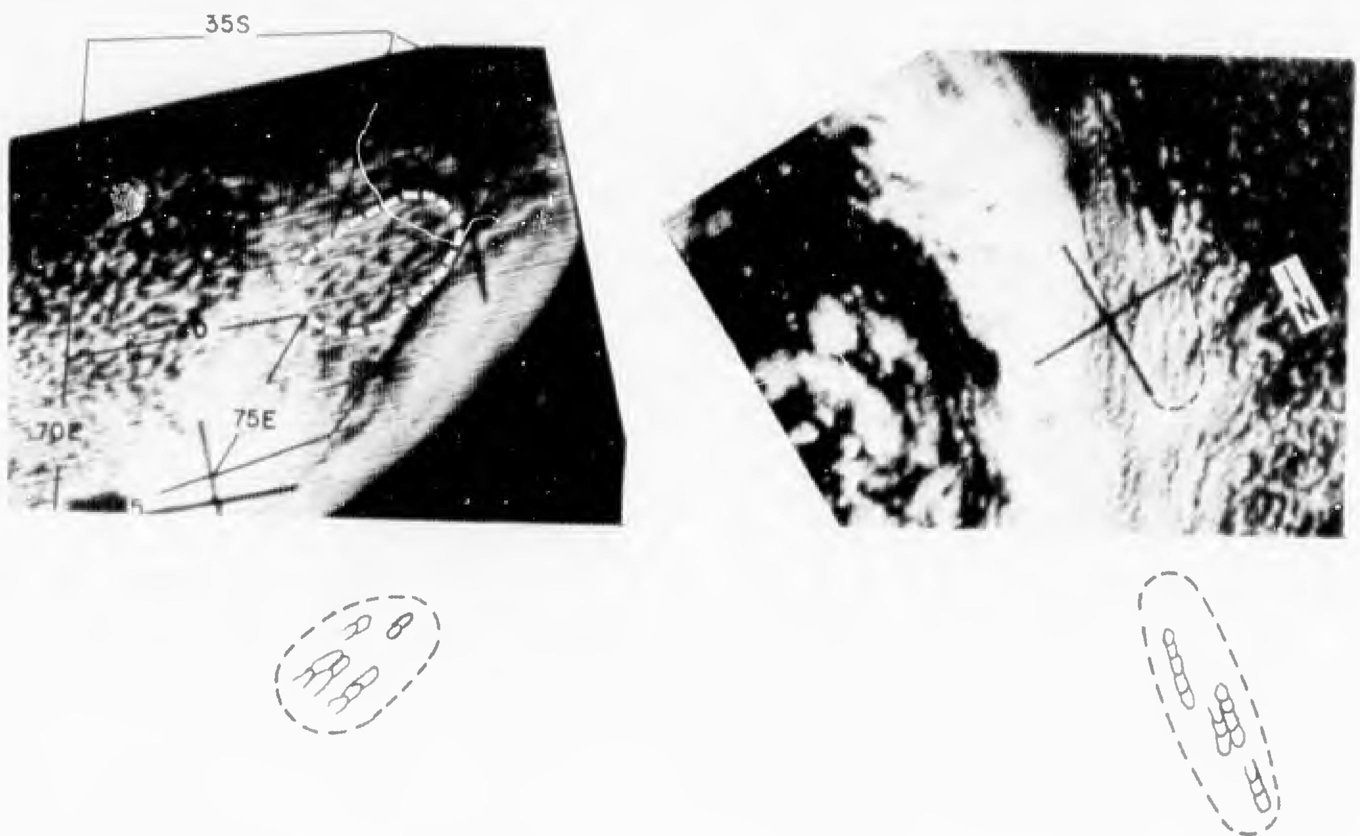

Fig. 8-8 Elliptical Chains

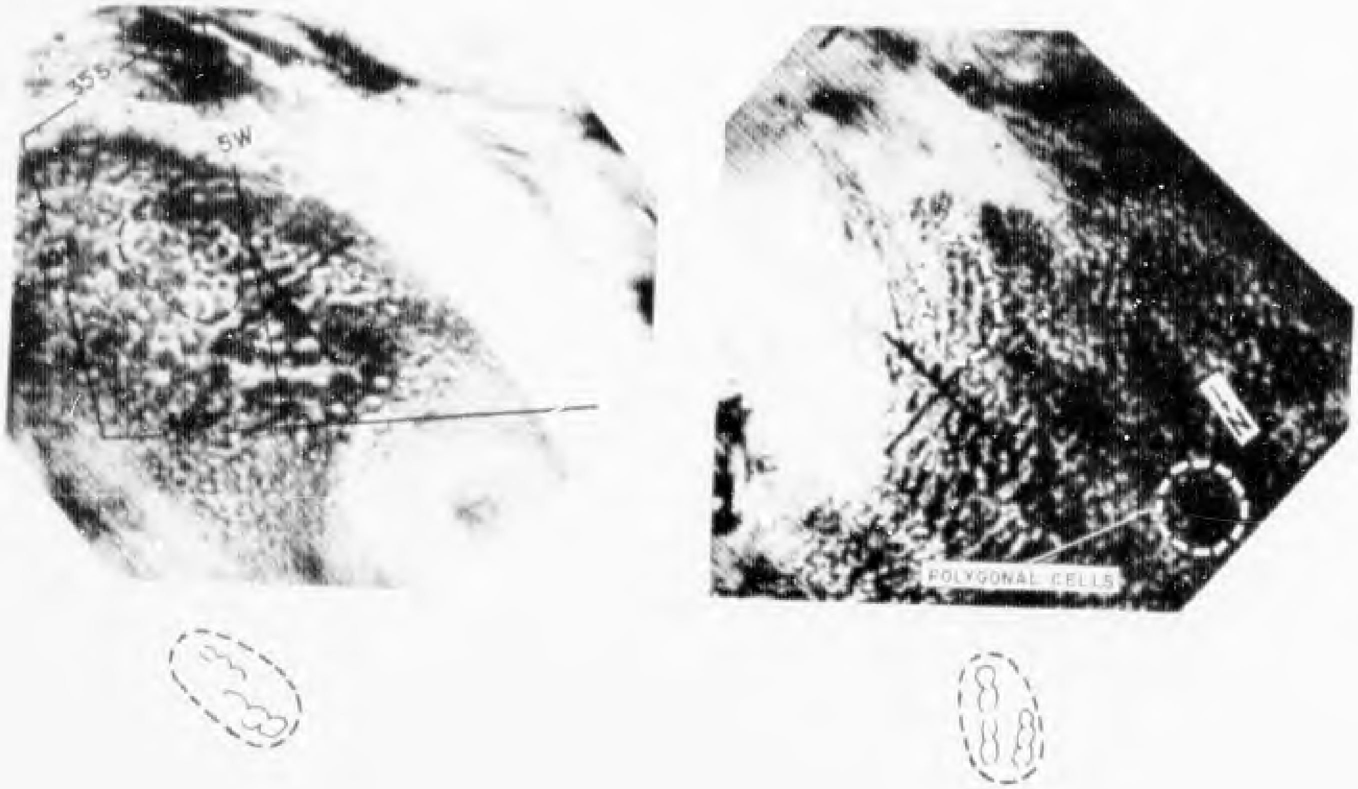

Fig. 8-9 Vermiculated

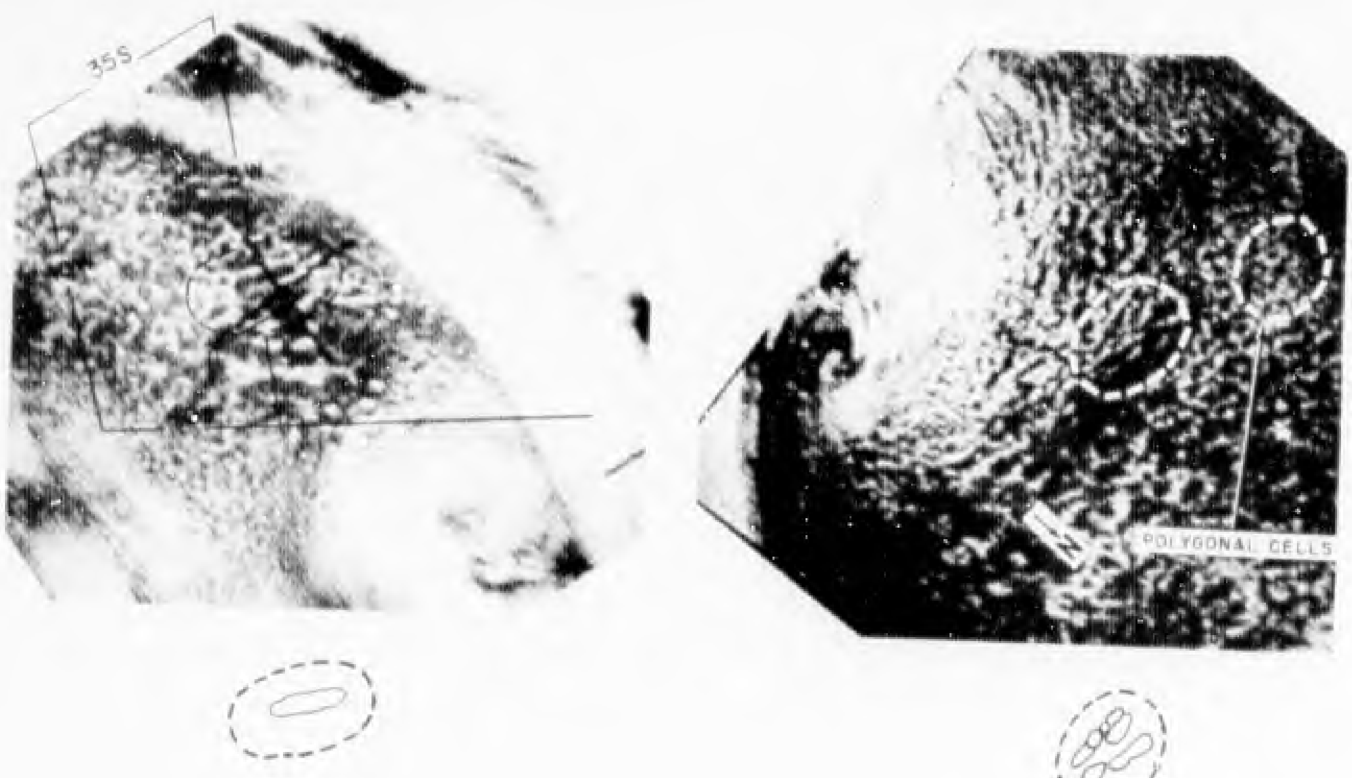

Fig. 8-10 Highly Elliptical

2) In the upper speed ranges of this category, the pattern assumes the appearance of parallel rows of undefined cloud elements. These rows are not continuous, but rather are composed of short segments. The wind direction is parallel to the orientation of the rows (Figs. 8-6 and 8-12).

While the categories described represent the patterns observed in the majority of the cases examined, there are variations which are significant and which cannot be treated in the same manner as those patterns. In some cases the cellular character of the cumuliform cloud patterns is indistinct or missing entirely. Such cases may be located in a weak trough of low pressure. The clouds may suggest a banded pattern which is apparently parallel to the reported wind, but there is no cellular character present. A weak trough of low pressure in such an area of cloud bands would imply the possibility of low-level convergence and, therefore, upward motion in this area. The reason for the lack of cellular character in such cloud patterns would be attributable to their mode of formation, i. e., by large scale vertical motions rather than by small scale convective action.

In a few cases it may be difficult to relate the cumuliform cloud pattern to the surface wind direction. In one such case, just behind a cold front, the pattern was apparently composed of cumuliform bands. Comparison of the cloud orientation with the surface winds suggested that they were at right angles to one another. The cumuliform clouds were probably growing through a several thousand-foot thick layer within which the shear vector was oriented differently from the surface wind. This vertical development may have been due to the proximity of the apparent frontal band; the subsidence inversion does not always appear in the immediate post-frontal region. This case illustrates an extreme example of a pattern which cannot be used directly to infer useful wind information.

8.1.2.3 Cirriform Anvils Originating With Convective Clouds

At times, faint cirriform plumes can be noted emanating from convective clouds or cloud masses (Fig. 4-9). These represent cirrus anvils, and their orientation provides information on the upper level wind and wind shear. *

* For a recent, detailed study on these matters, see also Erickson, C. O., 1964: "Satellite Photographs of Convective Clouds and their Relation to the Vertical Wind Shear," Monthly Weather Review, 92 (6), pp. 283-296.

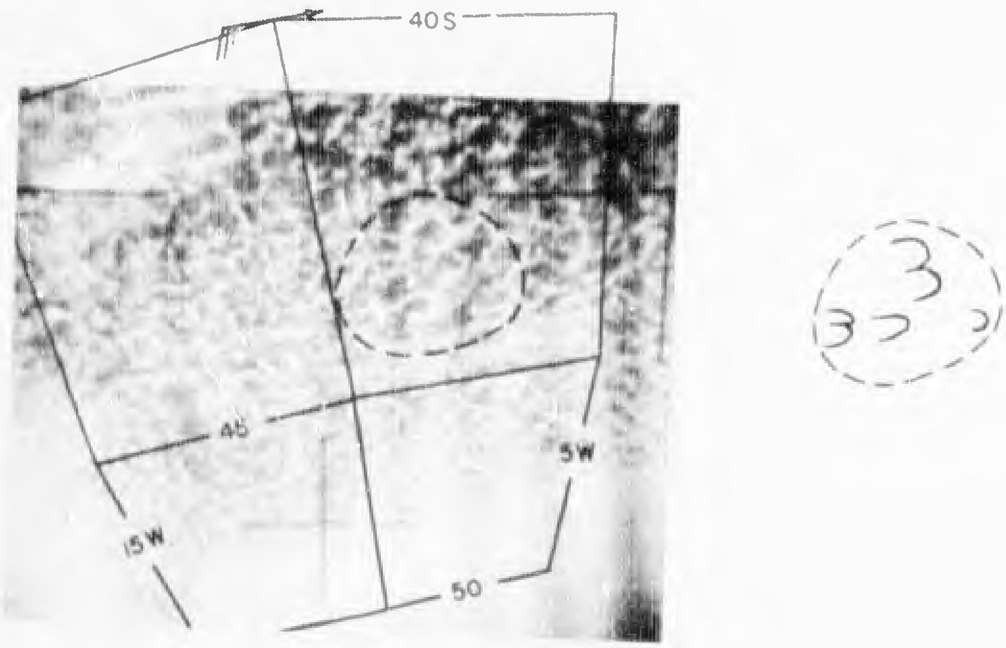

Fig. 8-11 Blown-out Ellipses

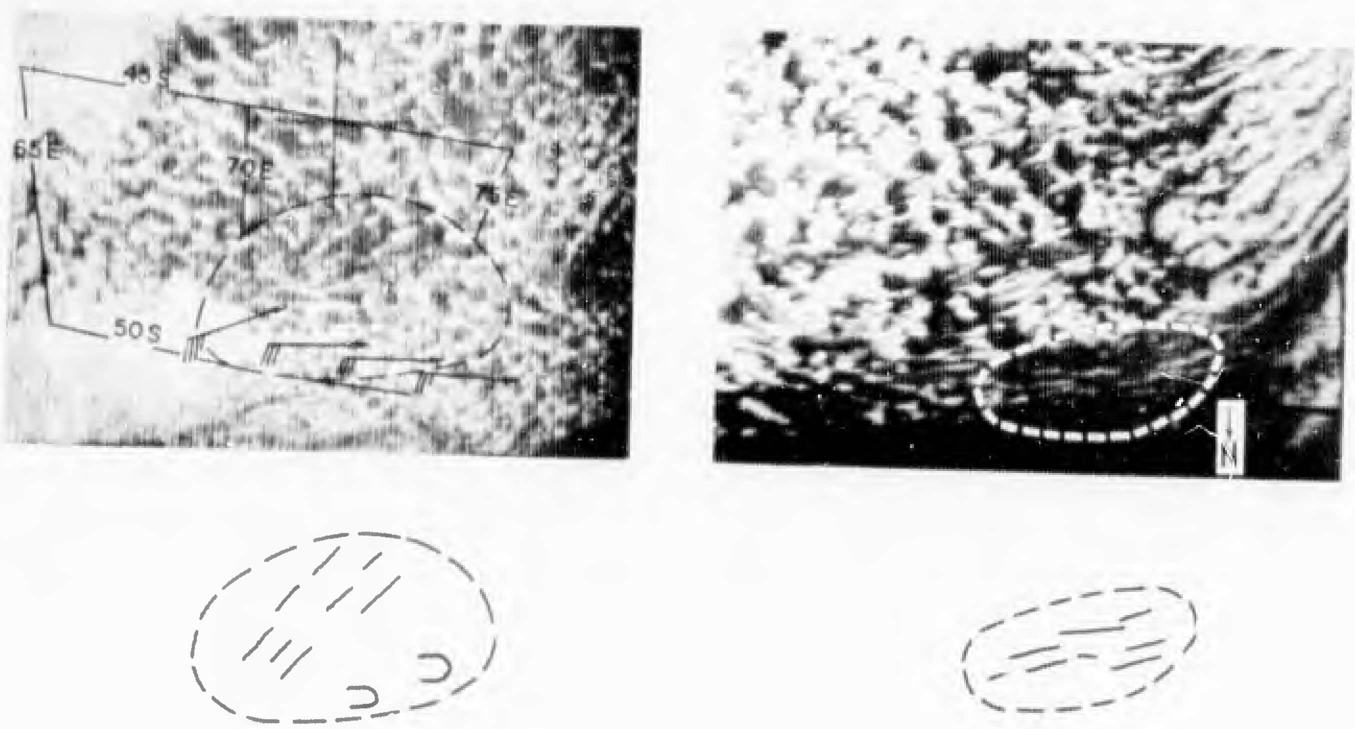

Fig. 8-12 Rows

Such plumes can frequently be seen associated with isolated cumulonimbus clouds both in subtropical regions, such as Florida and nearby waters, and in temperate areas; the plumes extend in the direction of the winds at levels of the order of 300 mb.[88] In the case of the major convective cloud masses representative of severe local weather such as are more common over the central United States, the horizontal dimensions of the cloud masses are often so large that they doubtless consist of a large number of convective towers which the camera cannot resolve into individual elements (Fig. 4-10). In these cases, the cirrus anvils may blend with the mass as a whole, helping to make it appear as a single large bright cloud mass and at times preventing identification of the cirrus plumes or deduction of the upper level wind direction.[41]

8.2 TERRAIN-RELATED CLOUDINESS

Topography can influence clouds and precipitation in many and complex ways. Lee waves, stationary and non-stationary, and the convergence or divergence induced by flow up and down valleys can produce clearing or cloudiness and instability. By inducing ageostrophic motions and differential advection of cold or dry air over warm or moist air, mountain barriers can lead to the release of instability. Once instability is released, the resulting circulation and vorticity production can, in themselves, induce additional convection.[61]

In several types of situations, mesoscale cloud features are directly related to terrain, or to air mass transitions in passing across a land-ocean boundary. Quite often these reveal significant information as to at least the direction of the prevailing air flow. Examples include upslope orographic cloudiness and downslope foehn clearing, crest patterns, lee waves, isolated lenticular clouds, fibrous plumes, coastal related but displaced cloud boundaries, and terrain induced arcs and vortices. Some of these situations are schematically summarized in Figure 8-13.[18]

8.2.1 Upslope and Downslope Effects (Including Those of Synoptic Scale)

Where air flows over a major mountain barrier, a band of orographic cloudiness is likely to be visible lying along and principally to the windward of the crest of the range. In the lee of the mountains, the downslope foehn effect may produce a clear area, perhaps even as a gap in an otherwise extensive cloud cover.[112] (Fig. 8-5A; note gaps in cloudiness in region of downslope flow into the Hudson and Connecticut River valleys).

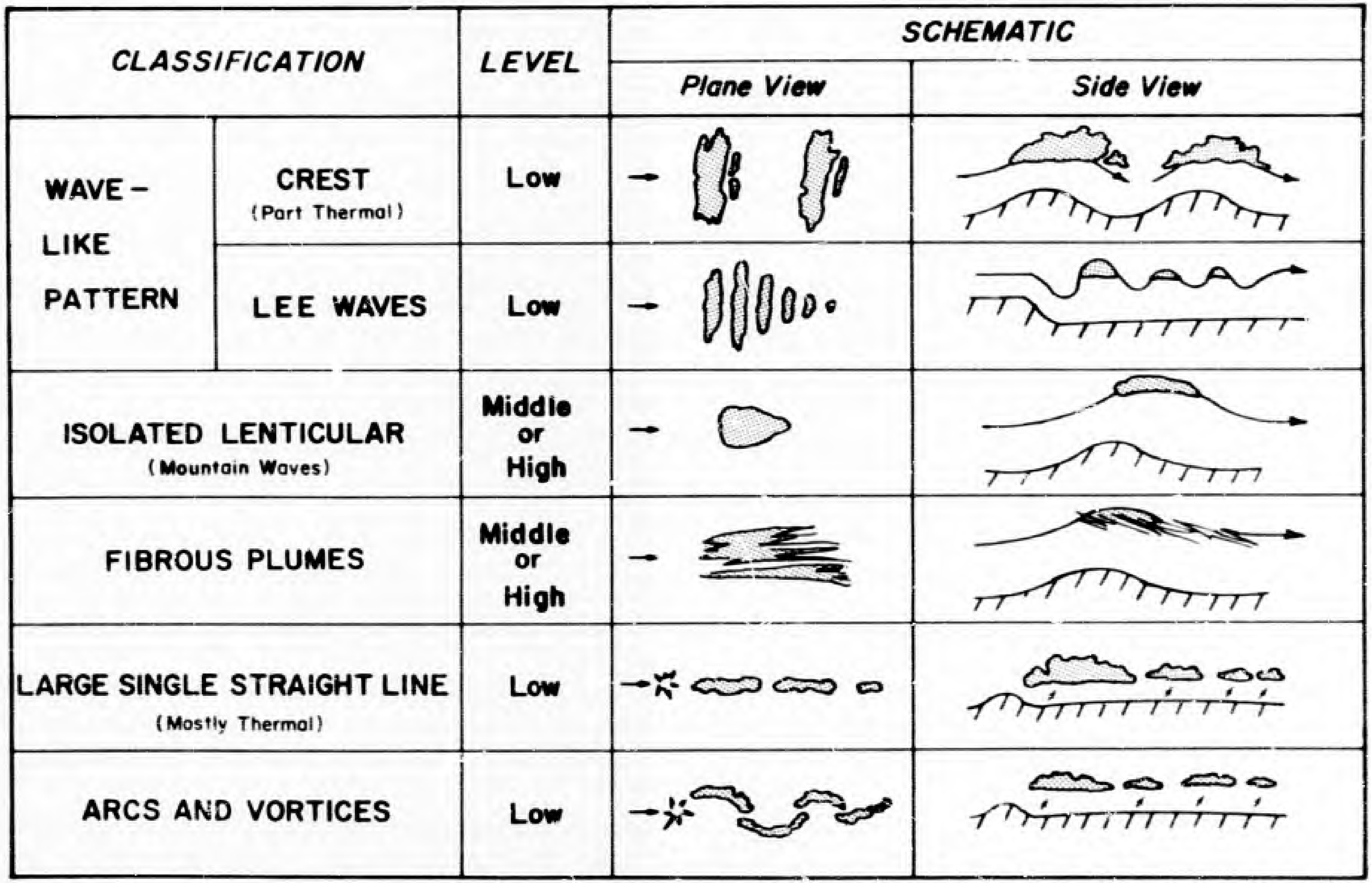

Fig. 8-13 A Schematic Summary of Some Terrain Related Cloudiness (From Reference 18, with Modifications)

8. 2. 2 Crest Patterns

Crest patterns[18] result from cumuliform clouds which form over mountain and hilltop ridges (Fig. 8-14). The thermal influences from heated slopes probably play an important role in their formation. After formation, they drift away with the wind and dissipate while new clouds form over the crest. This is in contrast to the lee wave pattern (see Section 8. 2. 3) which continues some distance downwind, and can help in differentiating between the two phenomena. Another difference is the cumuliform appearance of crest pattern clouds.

Crest pattern clouds can often be distinguished from cumulus in streets by their strong correlation with the topography of the ridgetops (Fig. 8-14). Crest pattern clouds may be confused with snowcover, which also may conform to ridgetops (see Section 9. 4). Snow usually appears slightly darker in tone. When snow cover maps are prepared from satellite photography, they greatly aid in making this distinction.

Crest pattern clouds are predominantly cumulus, cumulus congestus, stratocumulus, or occasionally cumulonimbus. The cloud bases are usually between 1, 000 and 3, 000 feet above the ridgetops, with the clouds generally not over 3, 000 feet in thickness, although in some cases greater vertical development may lead to the formation of cumulonimbus. In this event, these clouds appear somewhat brighter and larger than is common for crest patterns.

When crest patterns can be identified, it is reasonable to infer a lapse rate approaching dry adiabatic, weak vertical wind shear, and the lack of a strong component of the wind perpendicular to the slopes.[18]

8. 2. 3 Lee Waves

The term Lee Waves, as used here, refers to wave pattern clouds, over or downwind from hills or ridges, at altitudes not significantly greater than 10, 000 feet above the terrain below them. Mountain Waves,* as defined here, occur at levels

* In much of the meteorological literature, the terms Lee Waves and Mountain Waves are loosely used as synonymous.

near or above 20,000 feet and only infrequently produce clouds that can be seen in the satellite pictures.[18] The clouds associated with mountain waves will be discussed in Section 8.2.4.

Lee waves appear in the satellite pictures (Fig. 8-15) as approximately parallel cloud bands without cumuliform characteristics.[18] Since they require a significant component of flow over ridge-like obstacles, they form over or down-stream of mountains or even relatively minor hills or ridges. Typically, the clouds formed in the crests of the waves are rather closely and evenly spaced (Fig. 4-13). They are usually oriented nearly perpendicular to the flow and more or less parallel to the mountain range. The presence of the mountain range aids in distinguishing these formations from those in which cloud lines lie along the flow. The cloud bands may be straight or slightly curved.

These areas covered by such lee wave clouds are typically approximately oval in shape, with the major axis of the oval parallel to the wind (Fig. 4-13). Observed wavelengths have ranged between 3 and 11 nautical miles, with an average value of about 7 n. miles.[17,18]

Lee waves not only require a significant wind component across a terrain obstacle, but also an increase of the wind with altitude.[101] This vertical increase of the wind is often rapid, but usually there is little change in wind direction with height through a substantial layer above the top of the obstacle. Stability also usually plays a part in lee wave formation, the presence of a stable layer being favorable to wave formation.

Theoretically[101] a given wavelength can occur with many different combinations of wind and stability profiles. Observational evidence of the relationship between the wave length of lee waves and a mean layer wind speed,[20] including cases observed by TIROS, has however led to the approximate relationship:[50]

$$U = 6\lambda + 12$$

where U is the mean wind speed, in knots, between about the 850 mb and 200 mb levels; and λ is the observed spacing in nautical miles between the wave crests as depicted by the cloud lines. Some considerable scatter about this relationship is to be expected.[18] Over the range of most probable practical interest, this gives the following set of representative values:

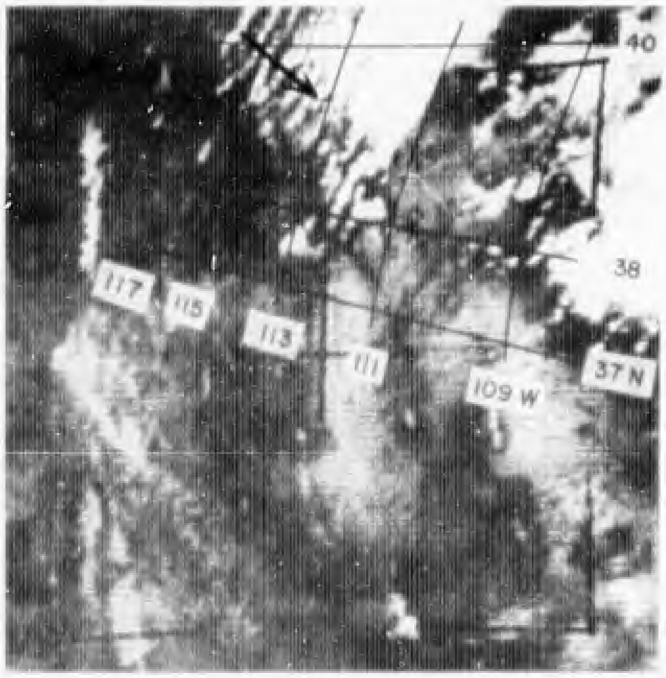

Fig. 8-14 Crest Pattern over the Ridges of Nevada, Top Left and Center (From Reference 18)

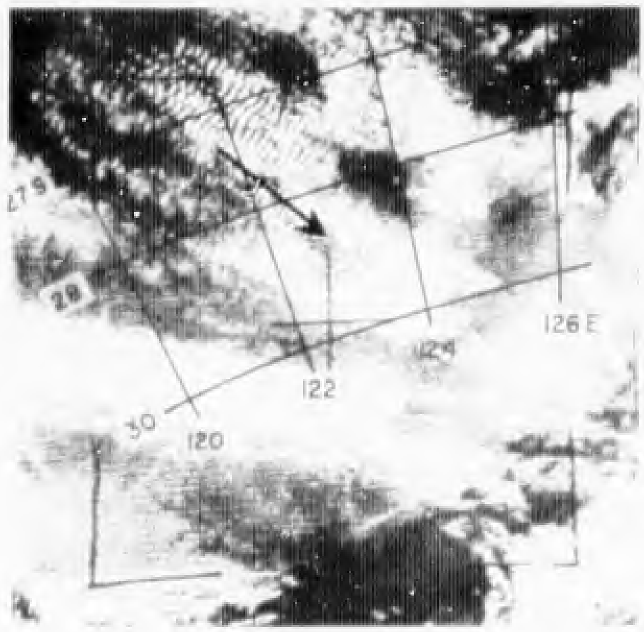

Fig. 8-15 Lee Waves over the Kimberly Range of Australia (From Reference 18)

Fig. 8-16 Lenticular Cloud at 35.0N, 118.8W over the Tehachapi Mts. of California (From Reference 18)

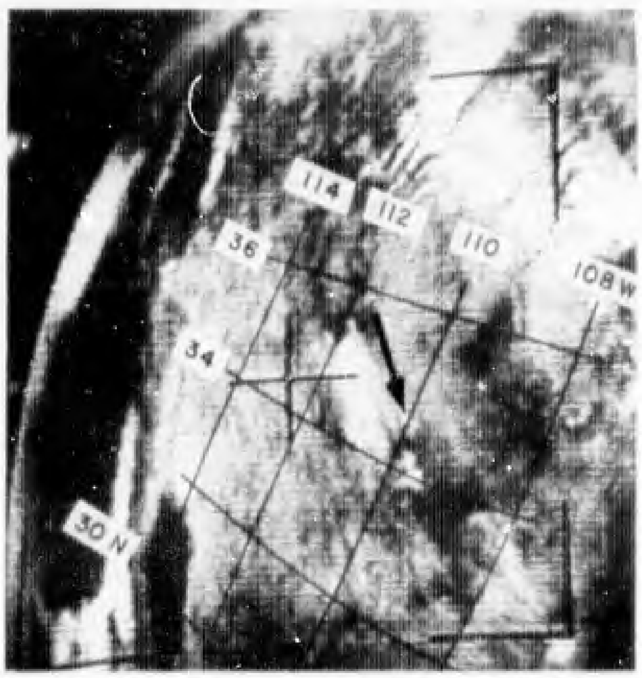

Fig. 8-17 Fibrous Plumes. Initial Formation is over the San Francisco Peaks, New Mexico (From Reference 18)

λ (wavelength in nautical miles)	U (mean speed in knots)
4	36
6	48
8	60
10	72
12	84
14	96

There are some indications in the data on which these results are based that, for wavelengths of 10 nautical miles or greater, the mean wind speeds in the above table should be reduced by about 5 knots.

The practical implication, from our point of view, is that on observing lee wave clouds on satellite photographs, one can assume that the wind near the level of the tops of the terrain obstacle has a significant component across the obstacle. Furthermore, there is almost certainly a pronounced increase in wind speed with height, but little change in wind direction with height. By measuring the spacing between the lines of lee wave clouds (wave length), one can derive a first approximation to the mean wind speed.[50] It seems likely that Air Weather Service forecasters can empirically develop improved relationships for their local or primary areas of concern.[18]

Other inferences are reasonable when lee wave clouds are observed.[18] The cloud type is most probably stratocumulus or altocumulus, although cumuliform characteristics are seldom visible in the satellite pictures. Cloud bases should lie between 3,000 and 10,000 feet above terrain, with the wave clouds 1,000-2,000 feet thick. An inversion will usually be present at the cloud tops, with near adiabatic conditions below. Low level thermal or mechanical turbulence is frequently observed.

Although the orientation of the cloud bands and the axis of the overall wave cloud area most frequently appears to be related to the wind direction, it appears that in some cases the orientation of the ridge may be the more predominant factor.[24]

8.2.4 Isolated Lenticular Clouds (Mountain Waves)

These cloud forms, also corresponding to the crests of waves induced by the flow over terrain obstacles, are only infrequently visible in satellite photographs because of their usual relatively small size and transparency.[18] When large and thick enough to be visible, they appear white and circular (Fig. 8-16). While appearing somewhat like a cumulonimbus, cumulonimbus are in most cases surrounded by cumuliform clouds of lesser or equal development (Fig. 4-23). Since only large and thick lenticular clouds are discernible, they will be found at levels near or above 20,000 feet with thicknesses over 1500 feet. A stable, moist layer of limited vertical extent is found at the cloud level.

Lenticulars form over or downwind from the terrain obstacle which causes the forced ascent of air. The wind direction tends to be constant through a deep layer when these clouds form. The air flows through the clouds, which remain quasi-stationary.[18]

Lenticular clouds, especially when associated with mountain waves, are significant for purposes of pilot briefing and short-period forecasting since it has long been known that the mountain wave is associated with one type of atmospheric turbulence. Recent investigation has suggested that where mountain wave clouds can be observed in satellite photographs, a high incidence of turbulence has been reported by pilots flying in those areas.[18,50] Other aspects of the feasibility of deducing clear air turbulence from satellite observations will be discussed later in this chapter.

8.2.5 Fibrous Plumes

Fibrous plumes[18] are also formed by condensation resulting from air ascending over a terrain obstacle (Fig. 8-17). These clouds appear as banded or fibrous, not cumuliform; they are streaky, often giving the appearance of smoke streaming from a definite source. The cloud forms initially as liquid drops, then is frozen to ice crystals which can continue to grow for some considerable distance downstream of the obstacle. These clouds are usually at levels near or above 20,000 feet, but less than 3,000 feet in thickness.

Lapse rates are nearly dry adiabatic from the mid-troposphere to the tropopause. Winds are typically strong at middle and high levels, without abrupt directional or speed shear in the vertical. Turbulence is of the "cobblestone" type similar to that frequently encountered near jet streams.[18]

8.2.6 Large, Single, Straight Lines

These lines of clouds are related to flow over islands (Fig. 8-18, where the lines are formed over Crete). They are believed to be primarily a result of thermal effects,[18] with the island surface significantly warmer than the surrounding ocean.

8.2.7 Coastal Related Cloud Boundaries

There are frequent discontinuities in cloud amounts and organization at coastlines. With most conventional observations on the land side and few or none on the water side, these discontinuities normally escape detection. At some places the clouds extend a short distance inland (Fig. 4-16). In other places the clouds end on or a short distance off shore (Fig. 8-5A). Moreover the character of the cloud mass may vary from one area to another (Fig. 5-5). Satellite photos reveal these discontinuities (or lack thereof) very clearly. The coastline itself is often discernible (Fig. 4-16) in the photo.[50,88]

Often, very cold air flowing off a land surface and out over warmer water forms a unique pattern of clouds (Fig. 8-19). For example, if a fall or winter arctic air mass has overspread the northeastern United States and moved out into the Atlantic behind a front, the edge of a cloud deck may often be seen over the Atlantic, some distance from shore, but obviously parallel to the coast line.

The cloud pattern between the front and the coast suggests the following process: The cold, dry and stable air flows from land out over the warmer water. The air mass begins to pick up moisture. Through heating from below and some mechanical turbulence a shallow unstable layer appears in the lower levels. As this process continues, clouds begin to form in rather fine, closely spaced lines along the wind (see Fig. 8-19), significant cloud density being reached 60-80 miles downstream from the coast line. As mixing takes place through a deeper and deeper layer, the cloud lines become more and more coarse and extend to higher levels. The forecaster, aware of this definite gap between the coast and the cloud-covered area from the data in the picture, can be considerably more specific than he could lacking such data.[45,50]

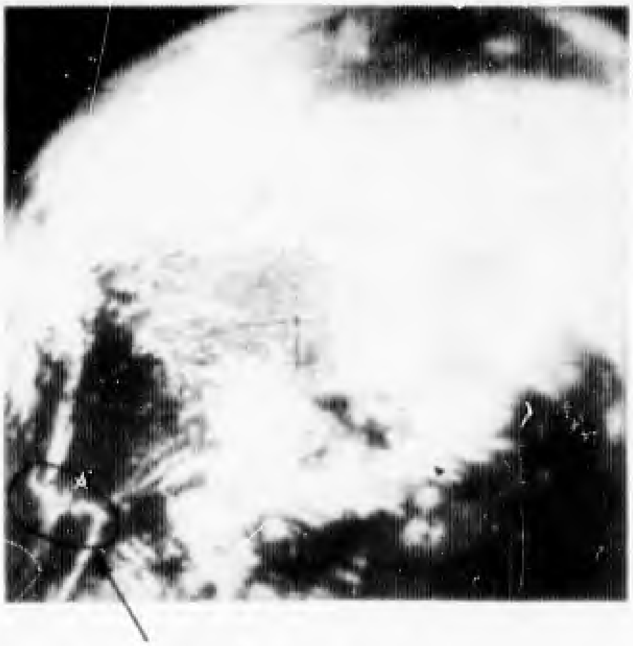

Fig. 8-18 Large Single Straight Cloud Lines Downstream from Island

Fig. 8-19 Clouds Formed as Arctic Air Flows Out over Atlantic Waters off Eastern U.S.

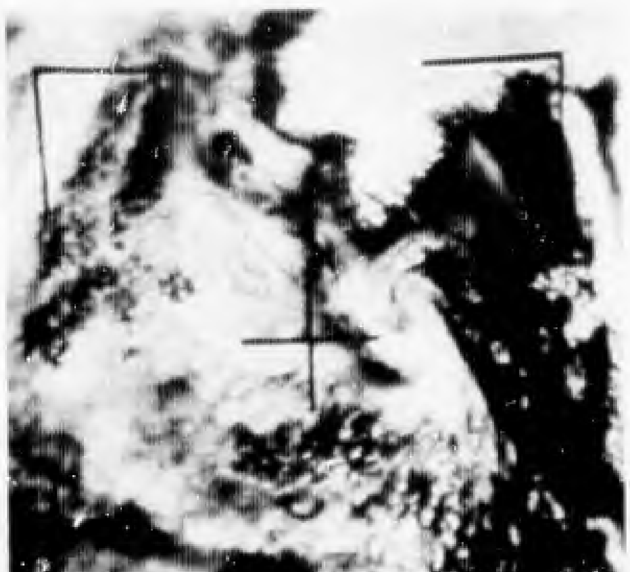

Fig. 8-20 Terrain-induced Vortex off Southern Tip of Greenland

8.2.8 Terrain Induced Arcs and Vortices

Vivid and unmistakable small scale arcs and vortices (Fig. 5-18) have often been noted in stratus clouds downstream from islands in the eastern portions of the subtropical oceans.[10, 56] Since they are associated with low wind speeds (the order of 15 knots or less) and with no more intense weather than the low ceilings normal to these fog or stratus-prone regions, their only operational significance is that, being induced by the flow over the islands and so lying downwind from them, they provide information on the general direction of the low level wind flow in the area. Some areas of clearing may often be found in the immediate lee of the islands. The forecaster should, of course, be sufficiently alert not to mistake these for the larger and obviously more intense cloud vortices associated with more significant weather. Usually this identification presents no real difficulties.

Small but distinct terrain induced vortices are also rather frequent to the east of the southern tip of Greenland (Fig. 8-20). Again, their differentiation from vortices associated with significant storms is not difficult.

8.3 CLEAR AIR TURBULENCE

As is well known, the delineation of jet streams,tropopause discontinuities, and shear lines is of major importance in the identification of areas likely to contain clear air turbulence. Over data sparse areas, satellite photographs can aid in this delineation. The general location and configuration of jet streams during cyclone development can often be inferred from satellite cloud photographs, as was discussed in Chapter 6. Deductions as to the relative distribution of tropopause heights may also be possible.

In the occluding cyclone stage (Figs. 6-10, -11) the region of lowest tropopause heights is displaced slightly to the west of the upper level low. The largest tropopause height gradients are adjacent to the jet stream axes on both sides of the low. The edge of the frontal cloud band on the east side of the vortex may mark the end of the steep gradient on the warm side of the jet stream axis.[103]

In the mature stage (Figs. 6-12, -13)the region of lowest tropopause heights is coincident with the closed cyclonic circulation at upper levels. The other elements of tropopause configuration are the same as for the occluding cyclone stage.

In the decay state (Figs. 5-14, 6-17, 6-18), the vortex cloud pattern is often weak and diffuse. The region of lowest tropopause height is coincident with the region of lowest pressure, both at the surface and aloft. There is no marked tropopause gradient over the entire area associated with the system.[103]

Accordingly, it seems possible to approximately locate the jet stream, and the regions of significant tropopause gradients using characteristic cloud patterns displayed during various stages of cyclone development. The relative intensities of the jet stream and of the tropopause gradients (features which are significant to clear air turbulence probability) are also functions of stage of development. In areas of sparse data, after these locations are established, the areas of probable or possible clear air turbulence enounters may then be charted using standard turbulence forecasting procedures.

More investigation is needed to establish the patterns of cloud cover (as photographed from a satellite) during incidences of clear air turbulence in other synoptic weather systems.[103]

8.4 OTHER MESOSCALE FEATURES

The use of the satellite pictures, or often of the nephanalyses, can provide information on the location and extent of ocean, coastal (Figs. 4-16, 5-5), and valley (Fig. 10-1) fog or stratus. In most cases, the synoptic observations provide a far lower quality of information, especially over the oceans.[112]

The ability to establish the precise boundaries of these areas is limited only by the ability to establish the geographic coordinates on the photograph and the accuracy with which such information is depicted in the nephanalyses. It should be pointed out that in many cases it is not possible to distinguish between fog and stratus on the one hand, and higher clouds on the other hand, from the brightness and texture of the image alone (see Chapter 4). However, the available conventional observations, together with the fact that the bright area has much the shape of a valley (Fig. 10-1), or of a coast line (Fig. 4-16), and that other near-by areas are (as would be expected in fog or stratus situations) relatively cloud free (Fig. 10-1), may give substantial support to the conclusion that there is in fact an area of fog and stratus.

In such cases, the satellite photograph complements the fragmentary picture given by conventional observations in a spectacular way. The surface observations reveal that this is an area of low clouds and fog but are incapable of indicating its areal extent with any precision. This precision can be furnished by the satellite data.[50]

8.5 PRUDENT USE OF SATELLITE OBSERVED MESOSCALE CLOUD FEATURES

The meteorological interpretation of mesoscale cloud features seen in the satellite pictures or entered on the nephanalyses must often be less complete or precise than for the synoptic scale patterns discussed in the previous chapters. Less mesoscale experience is presently available, since research analyses to date have tended to emphasize synoptic size features.

Often necessarily implicit in mesoscale interpretation is recognition of the type of cloud being observed. As pointed out in Chapter 4 reliable cloud type recognition from the satellite data is often impossible. Cloud type recognition appears to be much more required for mesoscale interpretation than for synoptic scale analysis; the general shapes of cloudy and clear areas convey considerable synoptic information.

In the absence of corroborating conventional data, caution should be used in inferring more than the location and extent of mesoscale cloud cover, unless a positive interpretation of the mesoscale situation can be deduced from the picture data or nephanalysis alone. Fortunately, in many cases a reasonably reliable interpretation is possible, as discussed in Sections 8.1 and 8.2. Where conventional data have been available, relationships between mesoscale synoptic features and the cloud coverage as observed by the satellites have generally been rather good.[41]

Further assisting the forecaster is the fact that, normally, mesoscale interpretation is more frequently required where other sources of data exist than in areas completely devoid of conventional observations.

QUASI-METEOROLOGICAL FEATURES

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CHAPTER 9

MISCELLANEOUS, QUASI-METEOROLOGICAL FEATURES

In addition to the clouds and cloud patterns that are visible in the satellite pictures, there are other features that may have meteorological import. These include sea and lake ice, snow cover and sun-glint reflections from water surfaces.

While these features may at times be of direct operational significance or have meteorological import, they are more likely to be of concern because they may be mistaken for clouds or may make it difficult to properly distinguish clouds or cloud patterns.

9.1 SUN GLINTS

When a satellite views a water surface at such an orientation that the sun's reflection appears, the size and brightness of the sun-glint can provide an approximate indication of relative surface roughness and so of wind speed. If the water surface is very smooth, nearly a mirror image of the sun can be seen (Fig. 9-1). If the water surface is relatively rough, serving as a diffuse reflector, the solar reflection is diffuse (Fig. 9-2), less bright, and so spreads more uniformly over the water surface.[42,58] The presence of the white caps, normally associated with rough water, may also be a factor, since they would tend to reduce the contrast between the area of expected sun glint and the surrounding water.

Unfortunately there are as yet no quantitative data relating the surface wind speed to the size of the reflection as seen in the satellite pictures; it is probably also a function of the nadir angle of view of the sun glint area.

In those cases where the sun glint is very diffuse (rough seas), as in Figure 9-2, care should be taken not to misinterpret it as a diffuse light grey area often indicative of scattered small cumulus (Fig. 2-8) or thin cirrostratus as seen against a water surface. One clue to identification of the sun glint is the tendency for the brightness to be symmetrical across the center of the glint, although the pattern should be longer towards, as compared to across, the direction of the sun from the satellite.

Fig. 9-1 Mirror Image Type Sun Glint Near Cape Blanco, West Africa (Compare with Fig. 9-2 Taken Only a Very Few Minutes Later)

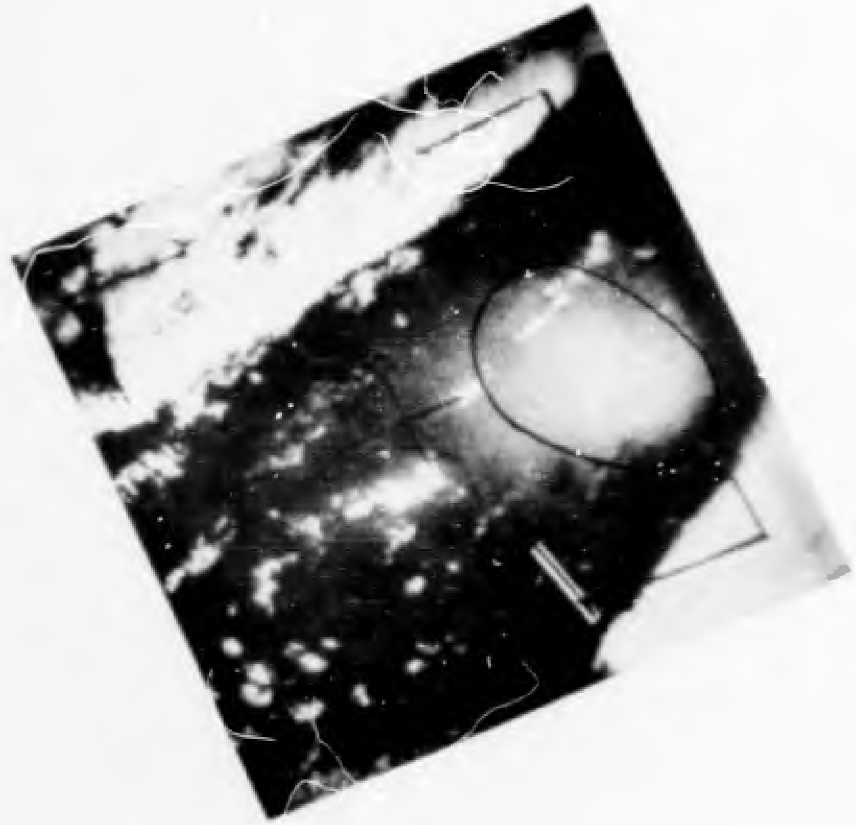


Fig. 9-2 Diffuse Sun Glint. (Note Movement of Sun-glint Area, and Diffusion, as Compared to that in Fig. 9-1)

9.2 SEA ICE

Sea ice has frequently been seen by TIROS, in the appropriate winter and spring seasons, near both polar extremities of its orbits.[2, 104, 116, 117] Ice observations have been especially frequent in and near the Gulf of the St. Lawrence (Figs. 2-6A, 2-10), Hudson Bay (Fig. 9-3), in and near the Sea of Okhotsk and off Hokkaido Island, and along the coast of Antarctica (Fig. 6-16, between 64-65S, and 140-145E). The extent and frequency of sea ice observations should increase greatly when meteorological satellites are placed in quasi-polar orbits.

Sea ice can usually be distinguished from clouds by its definitely white appearance, because it seldom changes much from day to day, and by its sharply defined edges and lines indicating breaks and leads.[50]

In addition to the necessity of being able to distinguish sea ice from clouds, the location and extent of the sea ice may be of direct operational significance. Further,knowledge of ice covered ocean areas may assist the forecaster in better predicting air mass conditions and/or modification in the polar regions.[5]

9.3 LAKE ICE

Ice-covered lakes usually appear as distinctive white areas in the satellite pictures[22], although a snow cover or some degree of roughening may be necessary to overcome the transparency of fresh, smooth ice. They can be distinguished from clouds by both the correspondence of the shape of the white area to the known geography of the lake (Figs. 2-10, 9-3), and by the lack of drastic change from day to day.[50] In the larger lakes, the pictures may also reveal the extent and location of ice-covered portions prior to complete freeze-up and during spring break-up.[22]

The presence, absence, and extent of ice may significantly influence weather conditions in the lee of large lakes, the Great Lakes being outstanding examples.[63, 87] The extent of lake ice cover and its persistence or past duration may also at times be of direct military significance.

Due to the resolution and contrast limitations of most meteorological satellite cameras, it may be difficult to distinguish thin or new ice, or ice covered with melt water, from open water.[22]

LAKE ICE

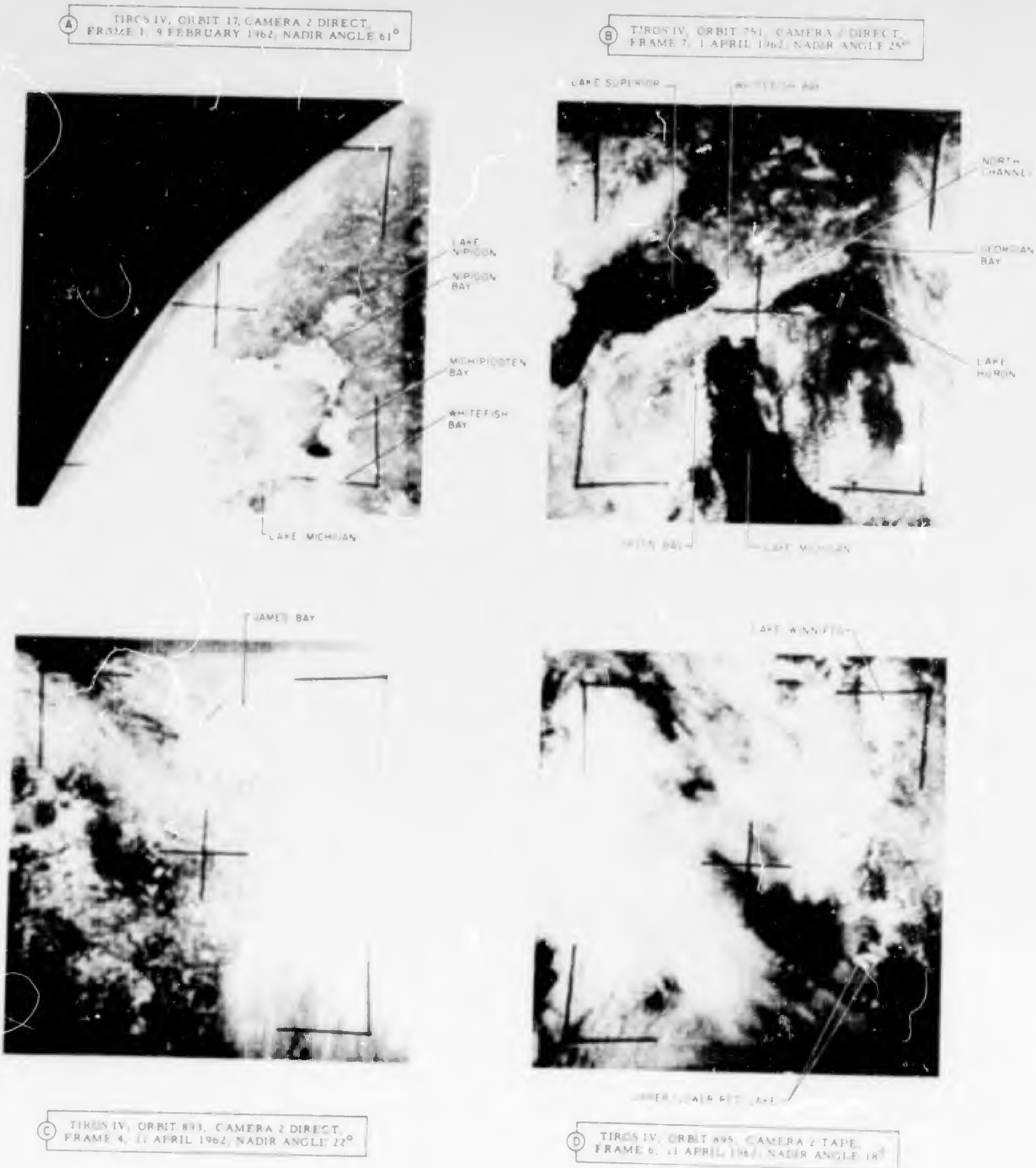


Fig. 9-3 Examples of Lake Ice as Seen in TIROS Photographs - (From Reference 22)

9.4 SNOW COVER

A problem of interpretation of clouds versus snow cover in satellite photographs arises from the fact that there is little difference in reflectivity between some cloud masses and snow fields. It is obvious that this becomes a problem primarily in the cold season and over land areas. In this respect it is fortunate that the largest volume of conventional data is available over land areas.[50]

There are several techniques which, when used together, can usually go a long way toward distinguishing between clouds and snow.

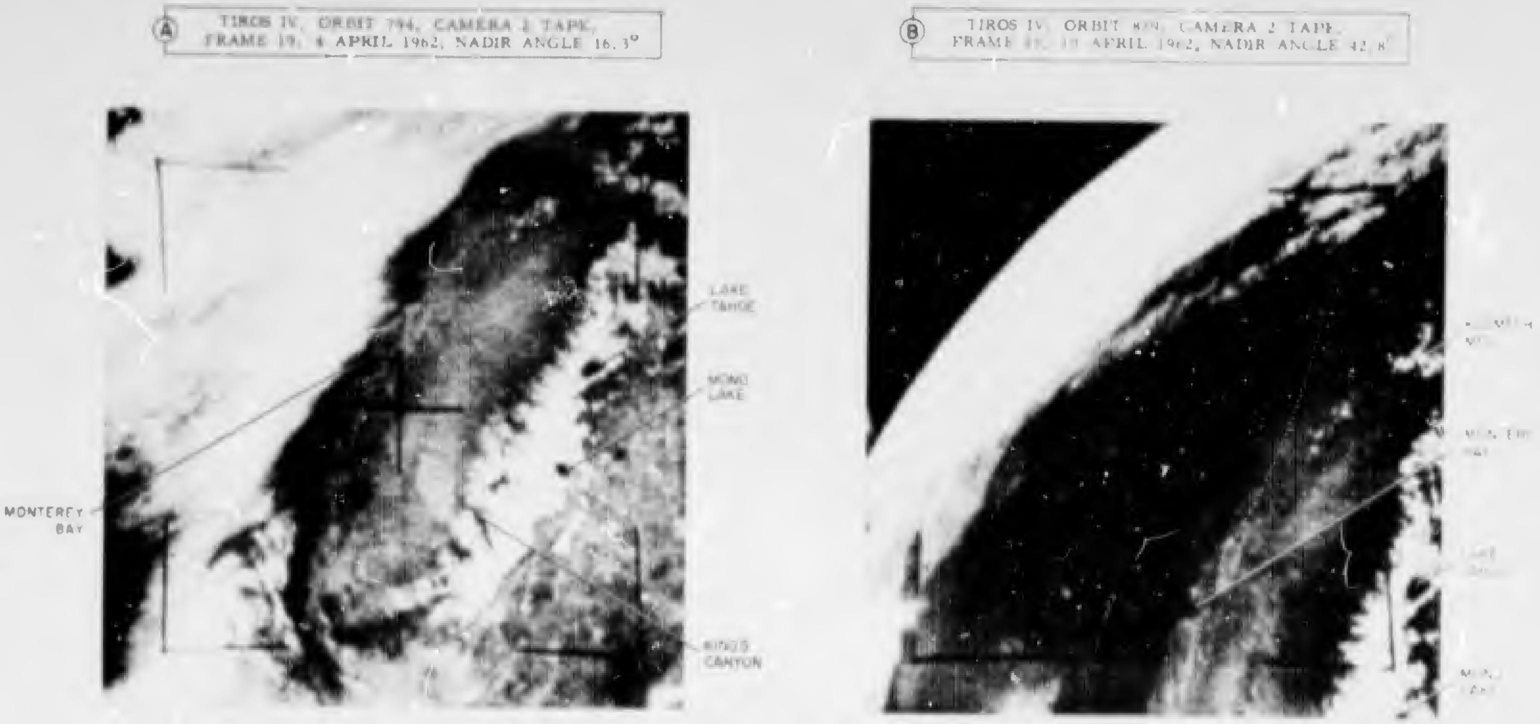
9.4.1 Characteristic Patterns

Satellite photographs have revealed characteristic patterns that indicate snow over mountain areas. These patterns arise because the mountain ridges tend to be snow covered, while the valleys tend to be relatively snow free (Fig. 9-4). Thus, the central ridge of the mountain range will usually show as an elongated bright area. Alternate ridges and valleys usually extend outward and at roughly right angles from the central ridge. Thus, in the usual situation, alternate bright and dark streaks, usually more or less well-defined, emanate outward from the central bright area.[36, 38, 104]

9.4.2 Stability of Patterns With Time

Since cloud patterns usually change in some degree with time, those patterns in which there is no detectable change with time should be suspected as being snow rather than clouds. Within the limits of the resolution of the system, comparing the view from adjacent orbits (some 100 minutes apart) may not be a reliable indication of the stability of the pattern for these purposes. On the other hand, comparing the views 24 hours (Fig. 9-5) or even several days apart should be extremely reliable. Of course, the possibility of fresh snowfall always exists.

SIERRA NEVADA



PACIFIC NORTHWEST

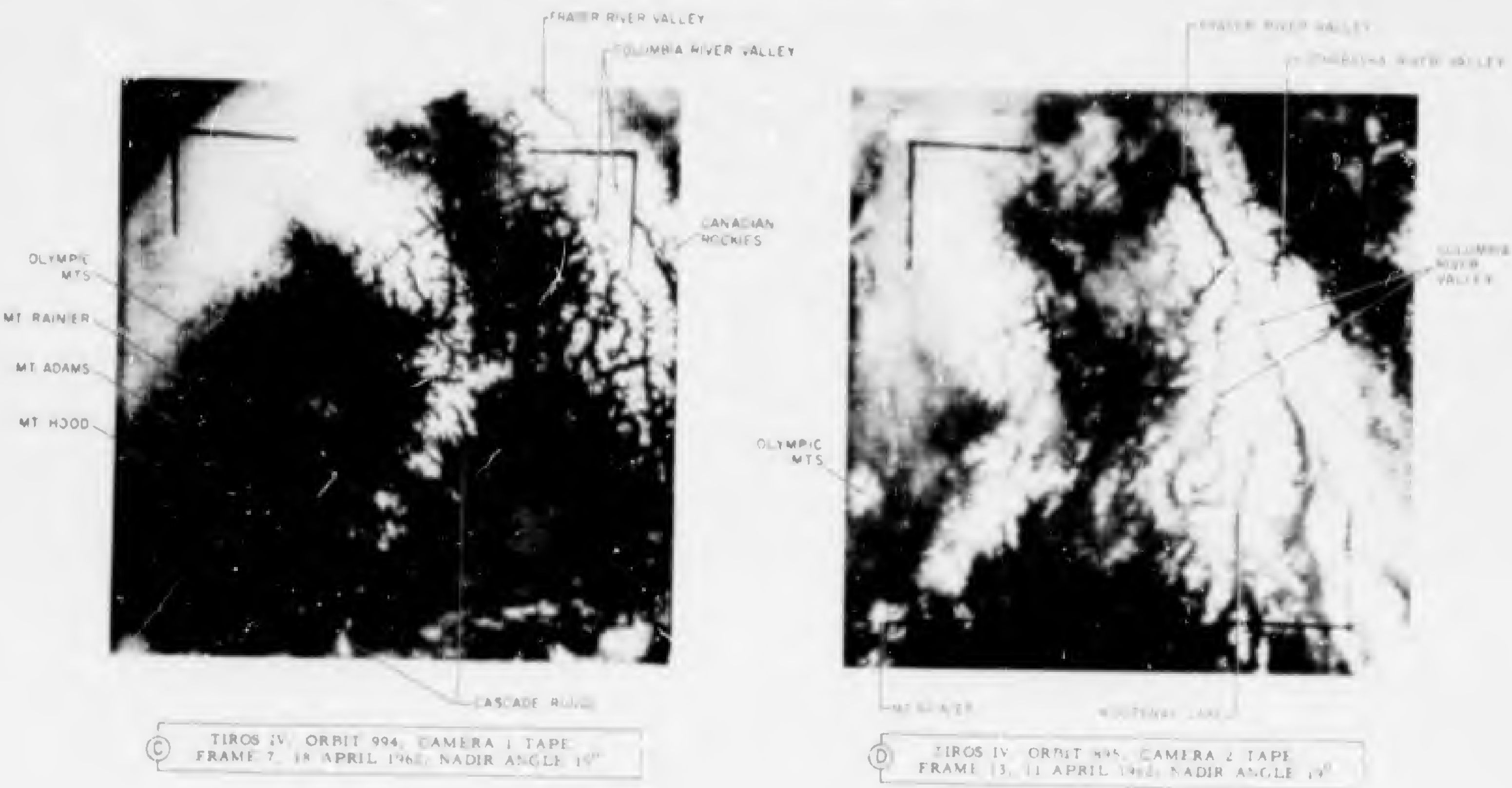
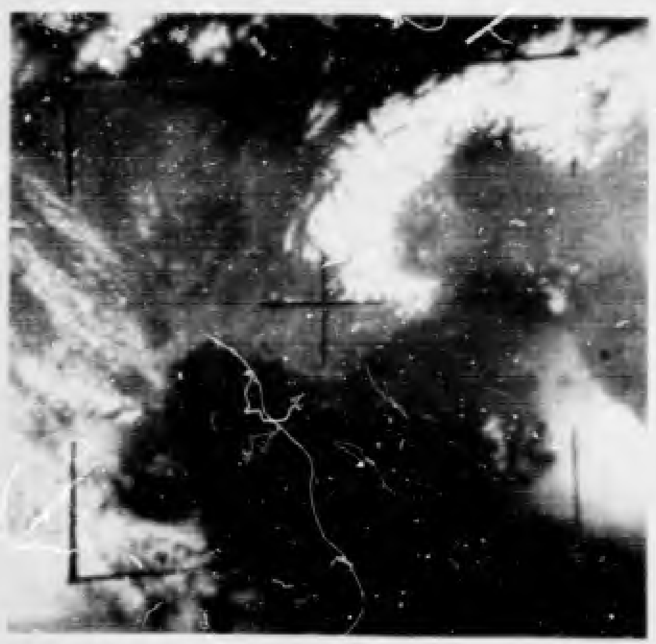
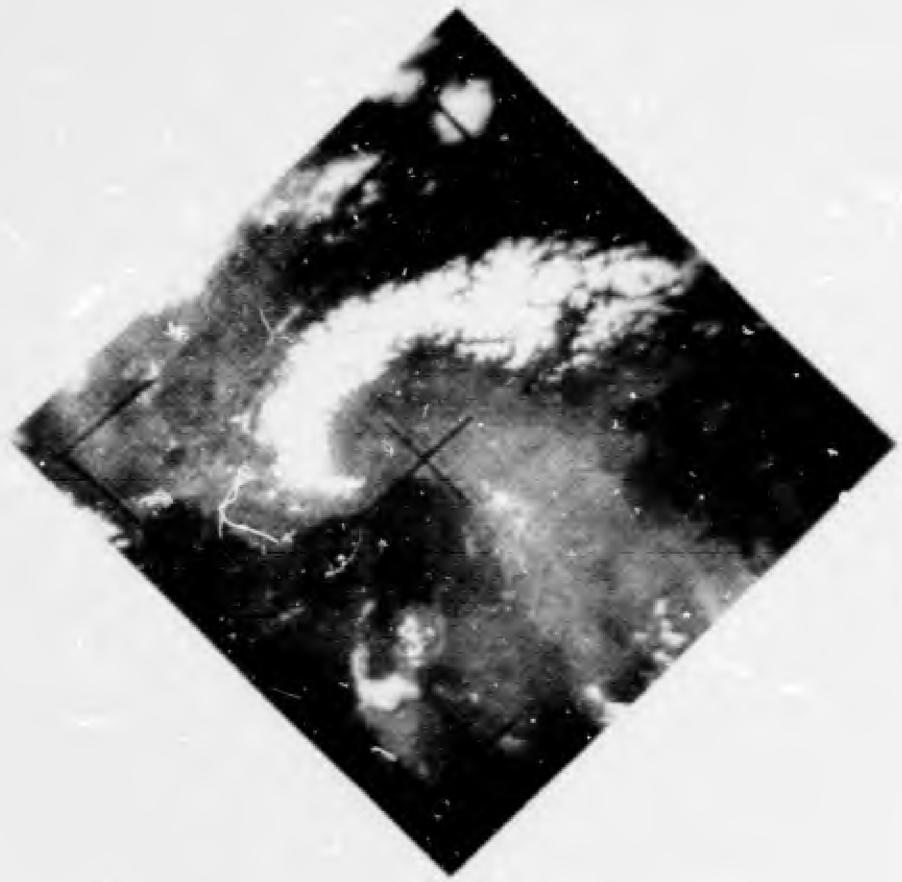


Fig. 9-4 Snow Cover in Mountainous Regions (From Reference 22)



0930Z, 25 April 1962



0855Z, 26 April 1962

Fig. 9-5 24-hour Continuity of Snow Cover in Mountainous Regions

9.4.3 Other Data

There are times, especially over the Great Plains and over similar areas outside the U. S., when the satellite photographs show considerable expanses of rather uniform bright area (Fig. 2-10). A study of available reported snow depths at synoptic reporting stations and reports of clouds as shown on the Weather Depiction Chart will usually help to reveal whether the general area is one of snow, clouds or both.[50]

With the aid of satellite cloud pictures it is often possible to delineate with considerable accuracy which areas are snow covered (Fig. 9-4), especially in the absence of dense evergreen forests.[22] By computing the change in area from week to week or month to month during the seasons of snow accumulations and of melt, information useful with regard to such operational problems as snow cover and flood forecasting can be provided.[38]

DATA INTEGRATION AND ANALYSIS

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CHAPTER 10

DATA INTEGRATION AND ANALYSIS PROCEDURES - EXTRATROPICAL

In the previous chapters of this report, emphasis has been placed on what the TV camera observes and the interpretations that can be made from these observations by Air Weather Service forecasters. This chapter will deal more specifically with suggested operational procedures for applying these data at Air Weather Service installations. Case examples are used to illustrate specific points. In addition, brief discussions of cloud patterns as anchor points for beginning synoptic analyses, a consideration of the value of climatological experience and available prognostic charts, and a set of abbreviated general guidelines for coordination and integration of satellite and conventional data are included.

As was pointed out earlier (but bears repeating here), the satellite is only a data gathering system, but one that provides a new source of important data for synoptic analysis and forecasting. The operational value of satellite data depends upon the relative adequacy of the conventional data available to the analyst, and hence varies widely with geographical location.

Even for areas of relatively abundant data, such as the continental United States, the satellite can often aid or improve synoptic analyses based principally on conventional data. In data sparse areas, the satellite data coupled with meager conventional observations will generally lead to a far better synoptic analysis than would otherwise be possible. Thus, in either case, the satellite and conventional data should be integrated in a manner convenient to the forecaster, and one that allows the maximum value to be gleaned from the combined data sources. It is worth recalling that a forecast can seldom be better than the analysis on which it is based.

10.1 UTILIZATION OF LARGE SCALE CLOUD PATTERNS

When considering the largest or quasi-hemispheric scale of analysis, considerable use is made of the fact that large masses of stratiform as well as cumuliform clouds, at multiple levels, have shown internal elongated and banded structures in the satellite photographs.[76*] Accordingly, the "streaming" appearance of the earth's cloud cover is strikingly evident when mosaics of satellite photographs or nephanalyses are displayed. Composites covering a significant fraction of a hemisphere usually dramatically reveal the families of mid-latitude cyclonic vortices, as illustrated in Figure 6-22 and Appendix B. A general sense of large-scale atmospheric motion is evident in such portrayals, clearly suggesting that some form of synoptic pattern in terms of major troughs and ridges can be deduced. Since they assist in the location of ridges and high pressure areas, even areas with an absence of widespread middle and high level cloudiness can be synoptically meaningful when related to those large cloud masses which can be more directly interpreted.

The following assumptions are considered reasonably valid when applied to analysis of macro-scale weather and flow patterns:

a. The orientation and distribution of major cloud masses reflect the broad-scale flow of the atmosphere. From striated patterns and elongated elements or "fingers" of clouds, the general direction of flow can be inferred.

b. In regions lacking extensive masses of stratiform, middle, and high clouds and showing only small-scale cumulus, the flow is generally assumed to be associated, within limits, with large-scale anticyclonic circulations. Under such circumstances, the placement of a ridge or anticyclone center is dependent on the estimated positions of troughs inferred from the cloud cover usually found east of the trough line, and on the expected climatological positions of the subtropical anticyclones.

c. Broadscale synoptic patterns as interpreted from satellite upper-level cloud patterns are fairly representative of the flow throughout a deep layer; i.e., above the convective levels and below cirrus levels. This assumption implies that macro-scale flow patterns exhibit relatively small directional shears within the middle layers.

* Reference 76 in its entirety is included in this report as Appendix B, and provides case examples of the matters discussed in this section.

d. Major cloud masses of the middle and upper troposphere can, in a very general way, be distinguished from low-level clouds.

Experience has shown that reasonable estimates of large scale circulations for at least the middle level in the atmosphere can be deduced in most cases from the satellite data, especially when climatology and analog techniques are judiciously applied. However, it is important to note that the use of satellite observations should complement, not replace, analyses based on available conventional data. But over sparse data areas, particularly oceanic regions where upper-air observations are few or non-existent, satellite-observed cloud patterns can serve as a most valuable aid in estimating the large-scale trough and ridge patterns, even if in many cases the satellite data alone are inadequate to permit unique solutions (examples are shown in Section 10.4).

Such analyses, when made with a nearly complete absence of other data, are necessarily subjective and have very definite limitations. Nevertheless, they can provide a means of obtaining at least a qualitative analysis where none could (or should) be made otherwise. Judicious application of physical and statistical climatology provides a necessary analytical control. A working knowledge of the relationships between weather and the field of motion is, of course, important, as well as the ability to broadly interpret the satellite observations of clouds in terms of types, elevations, and the effects of topography. Such capabilities have been found to develop after a reasonable period of experience in working with either the nephanalyses or the pictures themselves.

10.2 SMALLER SCALE PATTERNS

For locations such as weather centrals or forecast centers where adequate nephs and possibly some pictures are available, and especially for APT locations, cloud patterns on a scale approaching mesoscale can aid the forecaster. Forecast stations which have APT have the advantage that more detail is afforded by the pictures than is presently possible in the nephs. Such significant weather producers as squall lines or lines of large cumulus buildup (Figs. 5-22, 7-1) can often be seen in the satellite pictures and thus be more precisely located. Overlapping passes of the satellite in some areas may give some indication of the development or, with very accurate geographical location, even the movements of such features.

Large areas of stratiform cloud or fog, frequently found along coastlines (Fig. 4-16), can often be recognized in the pictures or nephs and thus the boundaries of such areas can be located. The boundaries of fog areas over land may also be apparent (Fig. 10-1) and aid the flight forecaster when choosing alternate bases for aircraft.

As the experience of the analyst working with the satellite pictures or neph-analyses grows, a greater variety of small scale patterns can be recognized and should lead to still further improvements in the synoptic analysis.

10.3 SUGGESTED TECHNIQUES FOR INTEGRATION OF CONVENTIONAL AND SATELLITE DATA

The use that an individual forecaster makes of the satellite data depends on many criteria, but the foremost of these is usually the relative amount or quality of conventional data available to him. The following suggested techniques were developed for optimum utilization of the data and are designed so they can be accomplished in the field. However, where available communications permit the dissemination of operational analyses from weather centrals to subordinate stations, these techniques can be even better accomplished at weather centrals since increased manpower and possibly actual pictures can be applied towards coordinating the satellite and conventional data. It is understood that Air Weather Service planning contemplates increased dissemination of central analyses in the relatively near future.

10.3.1 <u>APT Data</u>

The TIROS VIII APT system test (Fig. 2-12) was principally experimental with data available from only scattered orbits. Both because of the limitations inherent in an inclined orbit and spin stabilization, and of electronic problems, the operational application of the TIROS VIII APT data was limited. When APT becomes more routine, with a polar orbit permitting passes over a station to be read out on a regular basis, day to day continuity of cloud patterns can be observed and integrated into the synoptic analysis.* The particular value of APT derives from both the real time nature of the observation and from the detail available in the pictures as compared to the nephanalyses.

* As demonstrated by the Nimbus I APT data.

Some of the following suggested procedures may be used in a general sense but in modified form by stations having APT, especially in combining and integrating conventional and satellite data. Other procedures which better fit particular situations may evolve at individual stations. Since it is unlikely that the APT pictures and conventional weather charts will be at the same scale, it is usually best if either the significant cloud features are transferred to a weather chart (using the geographical grid lines in subjectively "eye-balling" the features to their correct locations and orientations) or the significant aspects of the conventional analysis are "eye-balled" to and sketched on the gridded APT picture (Fig. 2-12) or mosaic of pictures .

Because of the area and detail of the APT pictures, it may be particularly desirable to coordinate them with a sectional map for approximately the same time.

10. 3. 2 Neph Mosaics

Present practices allow only limited amounts of facsimile time for the transmission of nephs, and this and the nature of TIROS orbits have resulted in nephs being received at somewhat irregular intervals. Rarely are nephanalyses for two or more orbits, or even for the two modes (tape and direct) of a single orbit combined prior to transmission, although the set of pictures taken during the direct mode may be adjacent to and so in essence a continuation of the string of pictures taken during the tape mode. Nevertheless, these two sets of pictures may be treated at NMC as two separate nephs and transmitted separately, perhaps at times more than an hour apart.

At the present time, all nephs that do not cross the equator are sent on a polar stereographic projection while all nephs that cross the equator are sent on a Mercator projection which includes (in most cases) the area from 20°S to 20°N. Both maps are on a scale 1:20,000,000.

A definite deficiency in the present system is the nephanalyses being provided to the forecaster as limited pieces of satellite data for only small portions of the earth at a given time. Use of the data in this form is analogous to using sectional maps exclusively without the benefit of larger scale regional maps. * Although the

* By regional maps, we mean those covering areas approximately equivalent to that of the United States and contiguous portions of Canada, Mexico, and the Atlantic and Pacific Oceans.

satellite pictures for adjacent orbits, and the nephanalyses based on them, are approximately $1\frac{1}{2}$ – 2 hours apart, the coverage of adjacent orbits is usually contiguous or nearly so, and may even overlap.* Obviously, if the cloud depictions were available for areas more familiar to the forecaster (i.e., regional map size), cloud patterns and related synoptic features (i.e., trough, fronts, etc.) could be more readily associated. Fortunately, this can be rather easily achieved at either a weather station or a weather central.

To accomplish this larger scale depiction, it is suggested that available adjacent or nearly adjacent nephs be fitted together much as one would make a mosaic of pictures. Perhaps the easiest way is to paste or staple the nephs to a hemispheric chart for those nephs not crossing the equator, and to a Mercator chart for equator crossing nephs. An example of such a composite nephanalysis is shown in Figure 10-2.

Experience has shown that all nephs within $\pm$ 6 hours of a standard analysis time can effectively be so composited to obtain a neph mosaic, since the large-scale features of a cloud system retain their representative patterns for several hours.[12] The neph mosaic allows the spatial continuity of cloud patterns to be easily seen. The value of such large scale spatial continuity was discussed in Section 10.1 and is illustrated in Appendix B. Furthermore, use of time continuity through the comparison of cloud patterns from one day to the next is far easier. This continuity, especially over data-sparse areas, can be of major importance and provides clues regarding the development and movement of both tropical and extratropical weather systems.

It is suggested that, in general, a new 12 hour composite be started at neph times which are approximately six hours after each standard analysis time (i.e., at about 1800Z and 0600Z). In those cases where these specific intervals would separate the data from successive orbits near the area of prime interest, other time intervals may be more appropriate. As each new orbit is received, it should be added to the composite. Where overlap of the areas of adjacent orbits occurs, the neph with the time closest to the standard analysis time should be given preference unless the other orbit appears to provide a better depiction of the cloud patterns or the latest orbit shows significant subsequent developments.

* The separation is greatest near the equator, with overlap beginning and increasing as latitude increases.

10.3.3 Shading of Significant Patterns

The use of such neph mosaics by operational personnel at NMC has shown that pattern recognition is made easier if "Covered"(C) areas are shaded in color (for example, blue) and "Mostly Covered" areas (MCO) are also shaded in the same color but in a lighter shade.

This shading, in addition to any stippling* that appears on the nephs, makes the recognition of significant synoptic features easier since it helps in maintaining the continuity of cloud patterns both within a single neph and between adjacent nephs in the mosaic. As analysts gain sufficient experience, this shading becomes less essential but it is usually found to remain desirable in much the same manner that shading of precipitation areas on standard surface maps aids the forecaster.

10.3.4 Superposition of Conventional and Satellite Data

The following suggested procedures are not the only ones that will aid operational utilization of the satellite data but experience has shown them to be entirely satisfactory, and there are indications that future transmissions from weather centrals to field forecast stations are likely to resemble this format.

10.3.4.1 Oceans and Other Areas of Sparse Conventional Data

The greatest need for cloud data over oceans is usually at the synoptic scale, and it is suggested that the available nephanalyses be integrated with the major flow patterns and features from the concurrent appropriate sea-level or upper level synoptic analysis. Examples are shown in Figures 10-9, 10-11 through 10-14. These cases and general experience indicate that usually extratropical cloud patterns are most usefully correlated with the 500-mb chart. Other charts, such as a surface map or the 1000-500 mb thickness chart, can also be used; but as a general rule the integration of the neph mosaic and the 500-mb chart nearest to the neph time is found to be the preferable procedure. In a critical operational situation, however, if no fit between the cloud data and the 500-mb analysis can be achieved, a check with the

* Stippling, when it appears on the transmitted neph, defines those areas considered by the analyst preparing the neph as of the greatest synoptic significance. It should be considered a guide and not as an irrevocable decision.

surface analysis may be useful.

An important factor in simplifying the integration task is that both types of data are on conventional and compatible map projections. It is therefore relatively easy to place the cloud data within their broad synoptic setting by tracing the major features of the conventional analysis onto the neph mosaic.

The same procedures appear applicable to pictures acquired by direct readout (APT), even though rectification and scale considerations require "eyeball" transposition of the cloud data to the conventional analysis, or vice versa. Transposing conventional data onto the direct readout picture may be particularly valuable when there are details in the photo which can not be easily retained in a symbolic nephanalysis but which provide useful synoptic scale inferences.[50]

The USWB International Aviation Forecast Centers at New York and Honolulu (and possibly others) have used satellite cloud data as an effective tool for briefing international flights. If an up-to-date nephanalysis or satellite photograph covering all or a portion of the flight route is available, the briefer includes a copy with the standard flight folder. Pilot acceptance of this procedure has been enthusiastic.[50]

10.3.4.2 Land Areas with Adequate Conventional Data

Over the continental United States and other areas with adequate conventional data, there may be some question whether routinely combining the large-scale cloud patterns and operational synoptic charts (or simplified versions thereof) is a sufficiently useful standard procedure to justify the time and effort required. Generally, this tradeoff will hinge on the operational and weather situation. Obviously under generally fair weather, or more-or-less routine forecast conditions, the value to be gained is minimal. However, there will be many times when it is important to know, either for forecasting or flight briefing, precisely where the boundary of a synoptic-scale cloud system lies. If so, this portion of the satellite data is probably most appropriately transposed to the 500 mb chart, or perhaps to the Weather Depiction Chart. At other times, it may be of practical significance to know something about the organization of cloud elements within a particular cloud mass. If so, the cloud data are perhaps most appropriately transposed to the Weather Depiction Chart. These are two somewhat arbitrary examples, chosen because in both cases significant details of the synoptic-scale cloud systems are usually not revealed by conventional data.[50]

Specific procedures for synthesizing the smaller scale detail of cloud information with conventional data will necessarily depend on local station procedures. At stations where expanded scale sectional charts are plotted and analyzed, the appropriate details of satellite cloud information are probably best transposed to this chart. What information to transpose and how it is best done will depend on the nature of the meteorological situation as well as on the nature of the forecast problem.[50]

At times it will be useful to shade significant satellite observed cloud masses on the locally plotted sectional chart with the maximum possible precision. For example, subsynoptic scale features such as squall lines are probably best transcribed onto sectional charts.[50] When the satellite data are used at this scale of precision, consideration should of course be given to possible errors in the determination of geographic position. Although the relative positions of cloud masses are well depicted in the satellite pictures, their precise geographical positions (at the accuracy required for mesoscale application) may be questionable unless adjacent clear areas reveal landmarks which can serve as a check on the position accuracy.

10.4 CASE EXAMPLES OF INTEGRATED UTILIZATION OF CONVENTIONAL AND SATELLITE DATA

Four extratropical case studies were analyzed to provide:

1. Synoptic patterns representing all four seasons.

2. Data covering varying cloud patterns, but with emphasis on easily recognizable features such as vortices, cloud bands, etc.

3. Cases with data for successive days over the same geographical area, or successive passes over the same synoptic situation, to emphasize the advantage of continuity in time as well as space.

4. Synoptic situations with good conventional data coverage, in order to be able to confirm the matters discussed; but cases over oceans were also chosen since the utility of satellite data is greater in data sparse areas.

Nephanalyses and pictures are presented for cases in September, January, April and August. The January case utilizes unmodified nephs copied directly from those transmitted over standard US facsimile circuits. The remainder of the cases use nephs originally transmitted in the old (pre-January 1964) format; for the purposes of a presentation representative of present operational data, these nephs have been converted to the new format (Fig. 2-13). For a few orbits, these redrawn nephs were modified to more accurately depict the data in the corresponding TIROS photographs. The cases were chosen mostly at random, the only requirements being that reasonable satellite coverage be available, and that the cases chosen satisfy the criteria set forth above.

The order of presentation of cases was purposely chosen. The Autumn case is presented first for two reasons: (1) Particularly good satellite coverage was available and (2) the coverage was over the Continental US where excellent corroboratory data existed for the surface and the upper air. The Winter Case is presented next, again for two reasons. First, it employs unmodified nephs, just as originally transmitted in the new (1964) neph format, covering an area of sparse conventional data, and second, this case approaches, as closely as possible, an operational situation where the analyst would usually be working exclusively from the neph without the aid of the pictures themselves. The Summer case is presented next, again as a case where good conventional data exist , but one where a better analysis could have been drawn from the integrated data than from the conventional data alone. An example of how an APT transmission might aid the analysis is also shown for this case. These discussions are concluded with the Spring case because, of the four, it provides the best example of the advantages to be gained from integrating conventional and satellite data, using the procedures suggested, over a data sparse area.

The figures have been shaded, as suggested in paragraph 10. 3. 3, to illustrate the advantages to be gained from this procedure.

10. 4. 1 An Autumn Case

Excellent satellite coverage of the U. S. existed for many days during early September 1962, and revealed a sequence of synoptic patterns which lend themselves to easy presentation. Only two major patterns will be discussed here, although many other features can easily be recognized. A brief list of some of the other patterns considered significant in this case will be found at the end of this section.

Nephs covering areas of the United States and the adjacent Atlantic Ocean have been prepared in mosaic form for the period 7 September through 10 September. The two patterns that will receive major emphasis are the vortex that is over the northeastern US on 7 September; and the cloud patterns, associated with the 500-mb trough over the mountain states, which subsequently developed into another major storm.

10.4.1.1 The Eastern Vortex Pattern

Figure 10-1 is an unrectified picture mosaic of orbit 1147D taken from Reference 8. As discussed there, a major cyclone developed from a wave on the surface front in association with an area of middle tropospheric cyclonic vorticity advection. By 1200Z on 7 September, the well developed vortex is centered north of Montreal as depicted in the neph mosaic shown in Figure 10-2.

The top of Figure 10-2 (and of most of the subsequent nephanalyses in this chapter) shows the frontal analysis and surface isobars superposed over the neph mosaic, while the lower portion of Figure 10-2 shows the corresponding 500-mb contours and winds superposed over the same mosaic.

Thin arrows on the neph indicate a streaky appearance of the cloud bands, especially west and north of the apparent circulation center;and this streaky appearance when associated with a vortex in turn indicates a high probability that middle or higher clouds are present. The vortex can be recognized as an example of an "Occluded Mature Cyclone", as shown in Figure 6-12 of Chapter 6. Clear drier air is spiraling in around the vortex. This cloud pattern is almost always centered close to the nearly vertical axis of a storm, and the cloud and circulation centers (especially at 500 mb) are usually well correlated. In this case, good conventional data verify these findings.

Superposing of the conventional data (Fig. 10-2) indicates the 500-mb data fit the cloud pattern better than the surface data. The cloud band extending southward along the eastern side of the storm appears slightly downwind from a 500 mb trough line. The cloud pattern then extends southwestward into another area of cyclonic vorticity over Maryland and Virginia.

The band has a "frontal" appearance, but the surface data indicate no corresponding front over the northeastern United States or the adjacent ocean. Rather, this is a band of heavy cumuliform and stratiform cloudiness resulting from upward vertical motion associated with areas of thermal and vorticity advection. A cloud band along 31N, associated with a stationary front, is equatorward of and breaking away from the vortex-related band. Some tendency toward wave development on this front, associated with a mid-tropospheric vorticity maximum, exists in the widest part of the band over Alabama. Such wide band areas and their relation to frontal wave developments were described in Section 6.5.2.2.

The frontal band along 30N is primarily cumuliform in nature between 60 and 70W. A second band of cumuliform clouds to the south of the frontal band is probably related to convergence of the low level winds. Lines of cumulus near 25N,70W mark the low level flow in this area.

It seems reasonable to assume that the bright band across Louisiana, Arkansas, and eastern Texas joins with the covered area in central Texas shown in orbit 1148D. This cloudiness over Texas, Oklahoma, and Colorado is associated with a 500 mb trough system, and will be discussed in a later paragraph.

On rare occasions, when more than one satellite is transmitting pictures or when pictures over an area can be taken near sunrise and sunset, it is possible to get neph analyses for limited areas, corresponding to the standard upper air charts at both 00Z and 12Z. This was the case for 8 and 9 September, and the neph mosaic and 00Z maps for 8 September are shown in Figure 10-3.

The cloud vortex, centered at 55N, 73W, is easily recognized. The drier air has now spiralled further around the apparent center, and cumuliform bands are found to the south of the center. The cloud patterns now look much like the "Occluded Mature Stage", with dissipation about to start. However, the cloud pattern contains another notable feature which may be a clue to forecasting future tendencies of this vortex. Another band of cloudiness indicated as "+C" (heavy covered) can be seen in the neph on the upwind side of the 500-mb trough. This heavy cloudiness is just ahead of the small amplitude ridge over Minnesota and Manitoba and would not be expected from the contour pattern. Such cloudiness is normally indicative of an area of strong upward vertical motion, but here it appears in an area where the curvature of the contours is at best only slightly cyclonic and hence suggests little upward motion or perhaps even downward motion. Accordingly, the cloud pattern suggests that a short wave trough or vorticity maximum might be present in this area. Using this clue obtained from the neph, a closer inspection of the conventional data seems desirable. It can be noted that the 500-mb wind at Moosonee (approximately 50N,80W) has increased from 40 to 60 knots from 1200Z, 7 September to 00Z, 8 September (Fig. 10-3), and that a wind of 320°, 45 knots is plotted to the south of Moosonee. This second wind is apparently an aircraft report, since no standard upper air station is located in this area. The aircraft wind does not seem to fit the contour pattern, and presumably was more or less ignored. Considering both the heavy covered area which suggests a short wave trough in the middle tropospheric flow, and this aircraft wind, a forecaster might well look more closely at this situation and watch for subsequent downstream development.

Fig. 10-1 Unrectified Picture Mosaic of TIROS V, Orbit 1147D, 7 September 1962, 1250Z (Notable features are: well-developed vortex and clear area, valley fog patterns, and line of Cb)

This illustrates a type of situation that often arises over data sparse areas where a single and apparently incompatible observation is often neglected in favor of continuity. When the satellite and conventional data are integrated, further justification for altering the continuity pattern is often seen in the neph (or pictures) and a better analysis and forecast can be prepared.

At 1200Z on 8 September (Fig. 10-4), the cloud mass east of Hudson Bay remains associated with the now open trough pattern at 500 mb. It shows less organization, but the streaky pattern indicated by the double ended arrows in the "mostly covered" areas along 68W, and the persistent open areas, still permit recognition of the pattern. From the conventional analysis alone, one might guess that the 500-mb system would continue to fill. But the neph still shows heavy overcast downwind (east) of the trough position and so suggests continued upward motion associated with thermal and vorticity advection. Furthermore, in addition to the area of overcast which was upwind of the trough 12 hours earlier and which is now over the St. Lawrence Valley, a new area of overcast appears further upwind and gives evidence of a vertical motion field associated with some form of short wave disturbance moving into the system from the West. It can be related to the short wave trough near 57N, 95W. A flight forecaster concerned with the North Atlantic might well reconsider before forecasting the continued filling of this 500-mb system.

Figure 10-5 (00Z, 9 Sept.) shows that the 500 mb trough centered near 60N, 70W has not filled further. The cloud pattern is remarkably similar in appearance to what it was 12 hours before; further evidence that not much development or filling is taking place. Although no short wave can be seen in the contour field upwind of the trough, it appears from continuity and the plotted wind reports that a vorticity maximum may be near 50N, 75W, moving into the major trough area. Inadequate upper air observations in this area make it impossible to be sure of this vorticity maximum, but the rather large "blob" of heavy cloud coupled with the stronger winds at Moosonee and Toronto suggest this occurrence. A detailed analysis of this series of 500-mb charts and nephs suggests that the relatively heavy cloud mass now west and northwest of the 500-mb trough is probably associated with a vorticity maximum which has moved around the north side of the old closed system. By 00Z, 9 September, it is again near the main trough position. At this time, the major trough line seems to be along a line from 60N, 70W to 45N, 55W.

Twelve hours later, at 1200Z, 9 September (Fig. 10-6), the trough pattern seems to have sharpened considerably but the definition of the pattern is based on rather meager upper air data. In addition to sharpening, the trough seems to be oriented more nearly north-south along 65W. In this case, the cloud pattern shown by the neph seems to confirm the sharpening of this trough. A definite organization of the cloud pattern and a vortex at 65N, 63W is indicated by the neph. Pictures from orbit 1178T, shown in Figure 10-7, confirm the organization of the pattern shown in the neph. The cause of this sharpening of the trough is presumably the two areas of cyclonic vorticity mentioned earlier. The one that moved completely around the system now (1200Z, 9 Sept.) evidences itself in the organized cloudiness downwind of the trough. The second area is now evidenced by the heavy cloudiness approaching the trough line near 52N, 68W.

A blocking high is now developing east of the trough. The Greenland ice cap is clearly visible in the pictures from orbit 1178T. The lack of cloudiness results from the ridge and perhaps from downslope motion from the icecap; the analysis would not indicate such downslope motion, but it is suggested by the sharp cloud outlines in Figure 10-7.

No pictures were available for this area near 00Z, 10 September. By 1200Z on 10 September, Figure 10-9, the blocking high is located in almost the same position as 24 hours earlier. This high is now indicated by the large broken and clear areas, and the lack of cloud organization, as shown by the neph.

The heavy band downwind of the trough in Figure 10-6 is now breaking up; it is only "mostly covered" and of a cumuliform nature, with cirrus shearing off toward the northeast over Greenland. An area of overcast cloudiness near the trough line north of Labrador is still present, and is probably the remnants of the vorticity maximum which 24 hours earlier was at 52N, 68W (Fig. 10-6). With filling of the trough and decrease in both cloud amount and organization, a forecaster might now have a reasonable basis for forecasting a decrease in activity associated with this system. The trough continued to fill until 1200Z, 11 September (not shown), and then began to move rapidly eastward.

10.4.1.2 An Upper Level Development Over the Mountain States

The discussion will now shift back to Figure 10-2 and to the cloud patterns associated with the rather complicated upper air systems over the mountain states.

At 00Z, 7 September (not shown), the 500-mb map indicated a small closed low centered over northern New Mexico and a major trough deepening and moving eastward from a position (at 00Z) along a line from 60N, 120W to 50N, 130W. By 1200Z, 7 September (Fig. 10-2), two separate systems still appear on the map. The trough analysis over British Colombia now shows a closed isoline but only limited organization is apparent in the nephanalysis.

During the period from 1200Z, 7 September to and including 0000Z, 9 September, this system was analyzed by NMC as having a single closed contour. Throughout this period, it would be difficult to either confirm or deny, from the conventional data, the validity of this closed contour. Not until 1200Z, 9 September, was there an indication of an easterly component in the observed wind field on the northern side of the system. Prior to 9 September, the behavior and synoptic significance was more that of a trough than a closed low in the middle troposphere.

It will be shown that the cloud patterns for this period and beyond more closely resembled patterns usually considered to be associated with an open trough than patterns normally considered representative of a closed 500-mb system. It is suggested that the lack of cloud patterns characteristic of a closed low may have been an indication of a minimal closing off of the system during this relatively extended period.

Further to the south, over New Mexico, the conventional 500-mb analysis indicates a short wave is passing around the southeast side of the closed system. The cloud pattern again does not indicate a closed system, but it definitely appears to consist of middle or low clouds as shown by the cumuliform symbols on the neph. It appears from the combined neph mosaic and surface chart (Fig. 10-2) that this cloudiness is associated with the middle level system and not with any well organized surface or low level system. A rather wide area of precipitation is occurring with this southern system, which might not have been expected using conventional contour or pressure data alone.

Figure 10-3 shows the patterns for 00Z, 8 September. A large covered area shown on the neph and presumably extending north of the area of observation now correlates well with the position of the closed 500-mb center over the Canadian-US border near 112W. However, the cloud pattern does not fit well with the frontal analysis shown in the top of Figure 10-3. Precipitation in the form of snow and rain has broken out along the border. If this system were in a data sparse area, this cloudiness might not have been expected and the resultant precipitation might not have been forecast without the addition of the satellite data.

The closed 500-mb contour pattern formerly over New Mexico now shows as an open trough which has moved over Northern Texas and Oklahoma. Again the cloudiness shown on the neph correlates well with the 500-mb pattern but not very well with the surface pattern. Over a data sparse area, this "blob" of cloud might have given the analyst a clue as to the position of an upper level trough and an associated area of upward vertical motion which might produce precipitation. A trough which, at 1200Z, 7 September, was just moving onto the Oregon coast can now be seen both in the contour pattern and in the neph to be located inland over western Nevada.

By 1200Z on 8 September (Fig. 10-4), the southernmost system is still over northern Texas and Oklahoma and appears as a short wave moving around the major northern center which is now near 47N, 110W. A second short wave, formerly over western Nevada, now has slipped south to a position over southwestern Arizona but the neph does not extend far enough south at this time to permit a useful integrated analysis of this area. The short wave over Oklahoma now has a heavy cloud cover associated with it, but no closed circulation is apparent. A surface frontal wave shows signs of development in the area immediately downwind of the upper short wave. Moderate precipitation continues to be associated with this short wave. The cloudy area which is associated with the short wave now extends eastward into the cloudiness associated with the major trough over eastern Canada. The clouds still do not reveal the pattern usually considered representative of a closed circulation at 500 mb; and the trough along 110W is at best barely closed.

Another heavy cloud system moving into western Canada and the US can be seen on this mosaic near 130W. This cloudiness suggests a wave pattern with a somewhat greater amplitude than is shown in the conventional analysis.

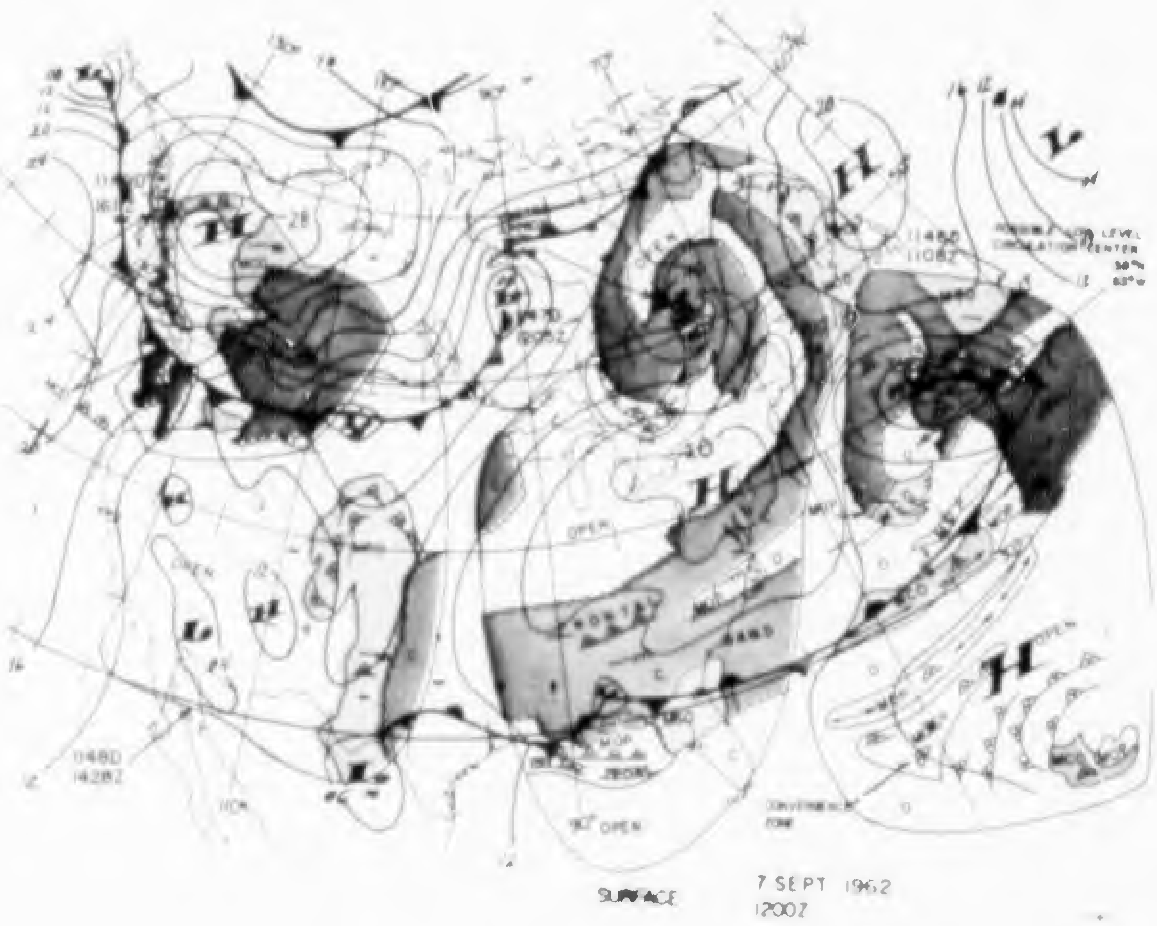
Figure 10-5 for 00Z on 9 September now shows the closed 500-mb center to be near 45N,108W. The cloud pattern as represented in the neph is no more than hook shaped. This hooked shape is usually characteristic of an open trough rather than a closed 500-mb system (see Section 6.2.3.1). A band now extends south and southwestward, along the associated trough and the short wave that was over southwest Arizona 12 hours earlier. This band does not fit the surface analysis; this suggests that either the frontal analysis is incorrect or that the frontal analysis was not a good indicator of the weather producing system in this area and situation.

The heavy cloud "blob" associated with the short wave moving around the eastern side of the major trough over Wisconsin, Illinois and Iowa is easily recognized and is the producer of substantial precipitation. This short wave is moving rapidly, and the difference in neph time (2240Z) and analysis time (00Z) probably accounts for the cloudiness which appears to be in the trough line. The cloudiness which appears to be west of the trough line is broken in appearance; since it is near the horizon in the picture, it might be slightly misplaced in the neph (see Chapter 2). The ridge line downwind from this short wave is clearly depicted by the mostly open area between the cloud masses associated with this trough and the 500 mb system farther to the east. Over data sparse areas, an analyst could use such an indication of breaks to place a ridge line.

The maps for 1200Z on 9 September, Figure 10-6, continue to show the good correlation of the cloud pattern to the 500-mb conventional data. The hook shaped cloud mass over the Dakotas with its trailing band downwind from the trough line is still clearly represented although not quite as evident as 12 hours previously. This is probably a function of the lack of coverage of this neph, and this illustrates how continuity from one map to the next aids in the recognition of the pattern. It is clear that this hook shaped pattern is associated with the 500-mb flow and not with the surface flow.

The cloud pattern associated with the short wave (which is over the Great Lakes and now well up the eastern side of the major trough) has taken on a more organized pattern and is now indicated in the neph to be a "possible vortex". A surface system often develops under or in association with such a short wave system, so that an indication of a possible vortex embedded in the cloud system is not surprising and probably marks the position of the surface system. A cloud mass showing some semblance of a band seems to be trailing south and then southwestward from this area just downwind of the trough. This band is more closely associated with the position of the front, as drawn on the surface analysis, than the remaining mass of clouds still further west. The low level center is complex in nature but centered approximately under the upper level short wave trough. Most of the precipitation of the system is associated with this short wave system. The cloudiness in advance of this short wave pattern extends well into the ridge at this time and seems to join the cloud area associated with the system to the northeast.

Figure 10-8 is the neph mosaic and conventional maps for 00Z on 10 September. By this time the winds north of the center are from 080° and now leave no doubt that the principal center at 500 mb has a closed wind circulation. Some increase in the cloud organization is apparent but the pattern still does not resemble the pattern expected for a closed 500-mb system. A cloud band still extends to the south and is just downwind of the longer wave trough. The short wave trough has now moved into the area of the long wave ridge, causing the breakdown of the ridge and a more zonal flow pattern. The covered area west of Montreal near 48N, 75W is probably associated with the remnants of this short wave trough. The breaks in the cloud pattern near Lake Huron probably indicate the position of a weak ridge. Wide



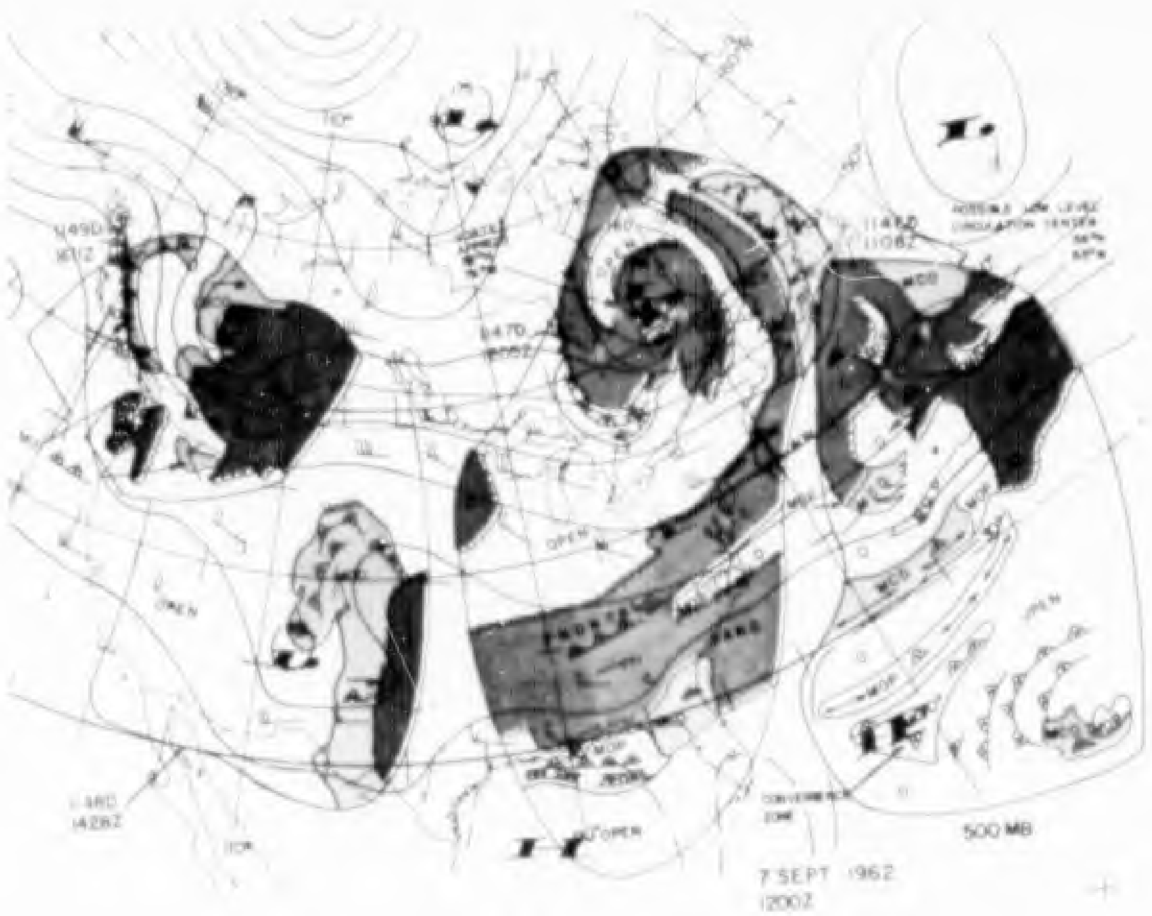
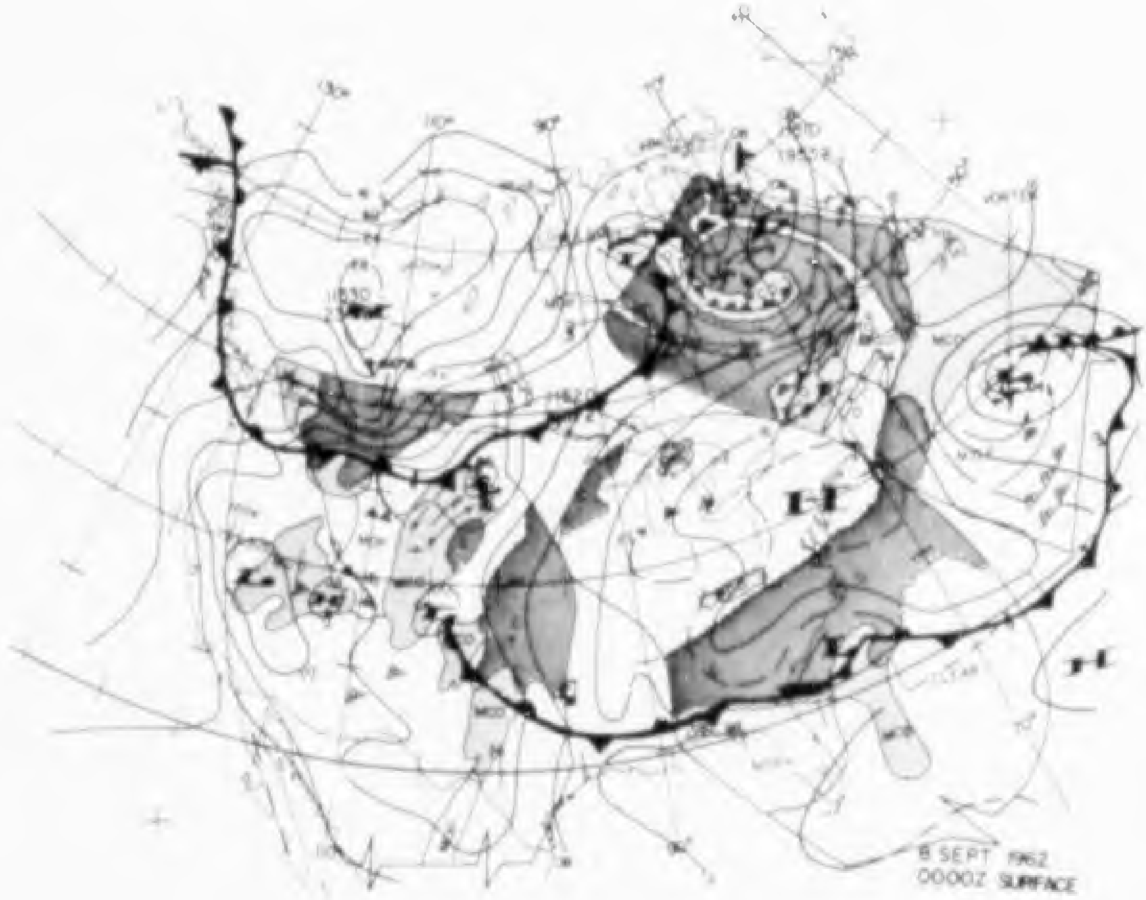


Fig. 10-2 Neph Mosaic with Superpositioned Conventional Surface and 500-mb Analyses for 1200Z, 7 September 1962



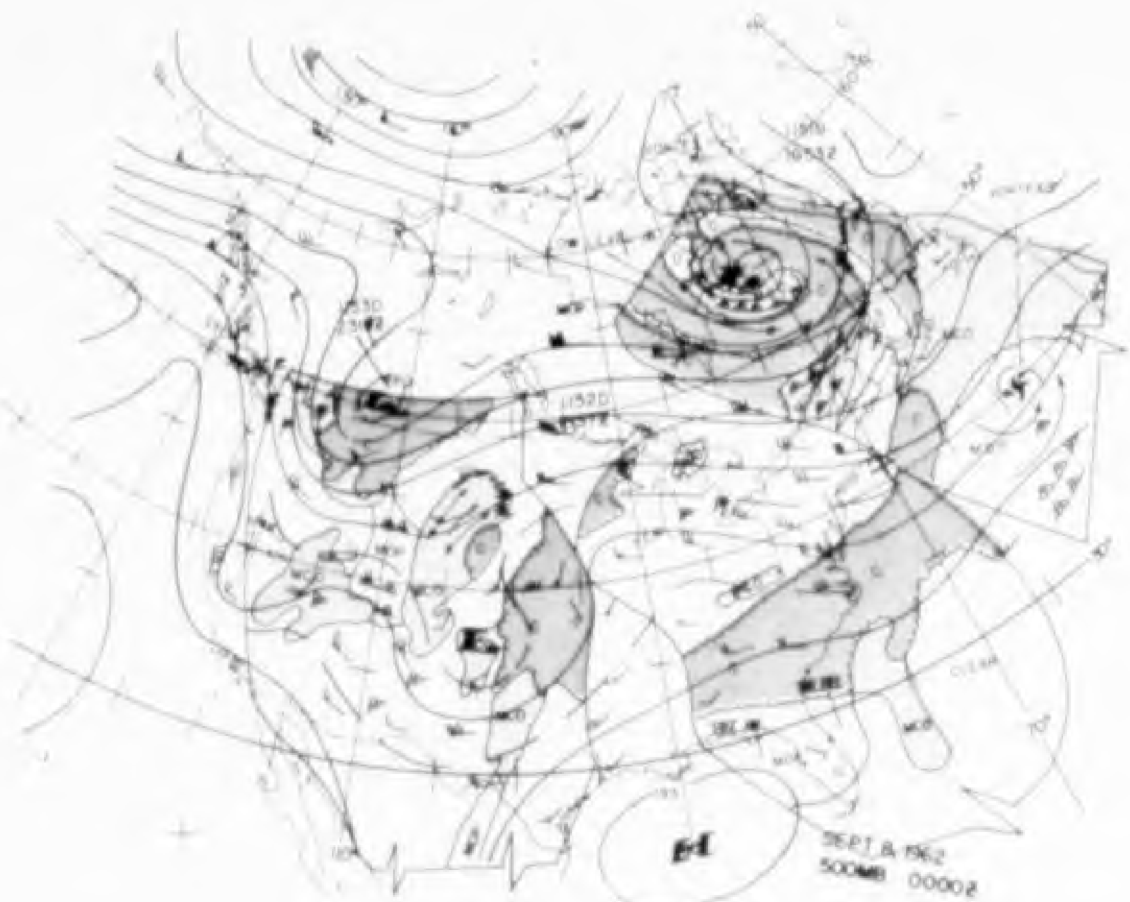
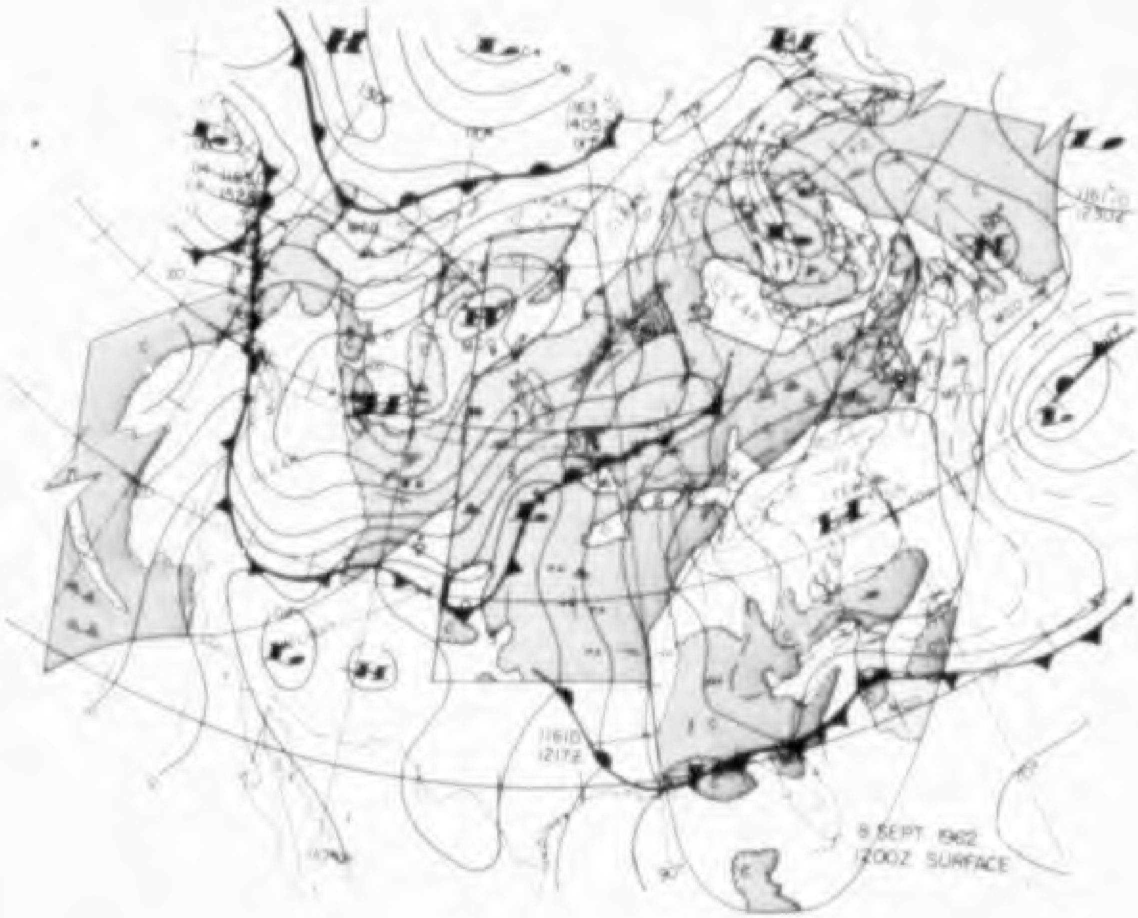


Fig. 10-3 Neph Mosaic and Conventional Analyses for 0000Z, 8 September 1962



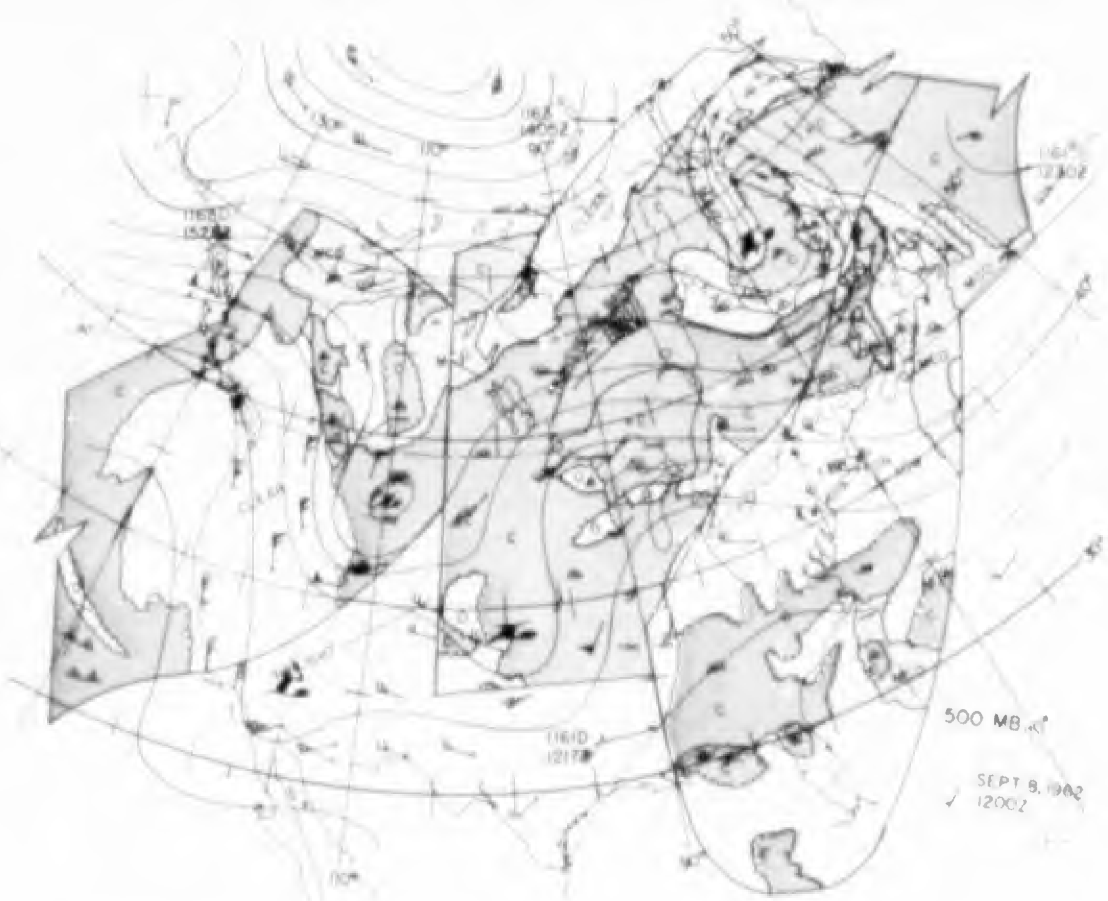
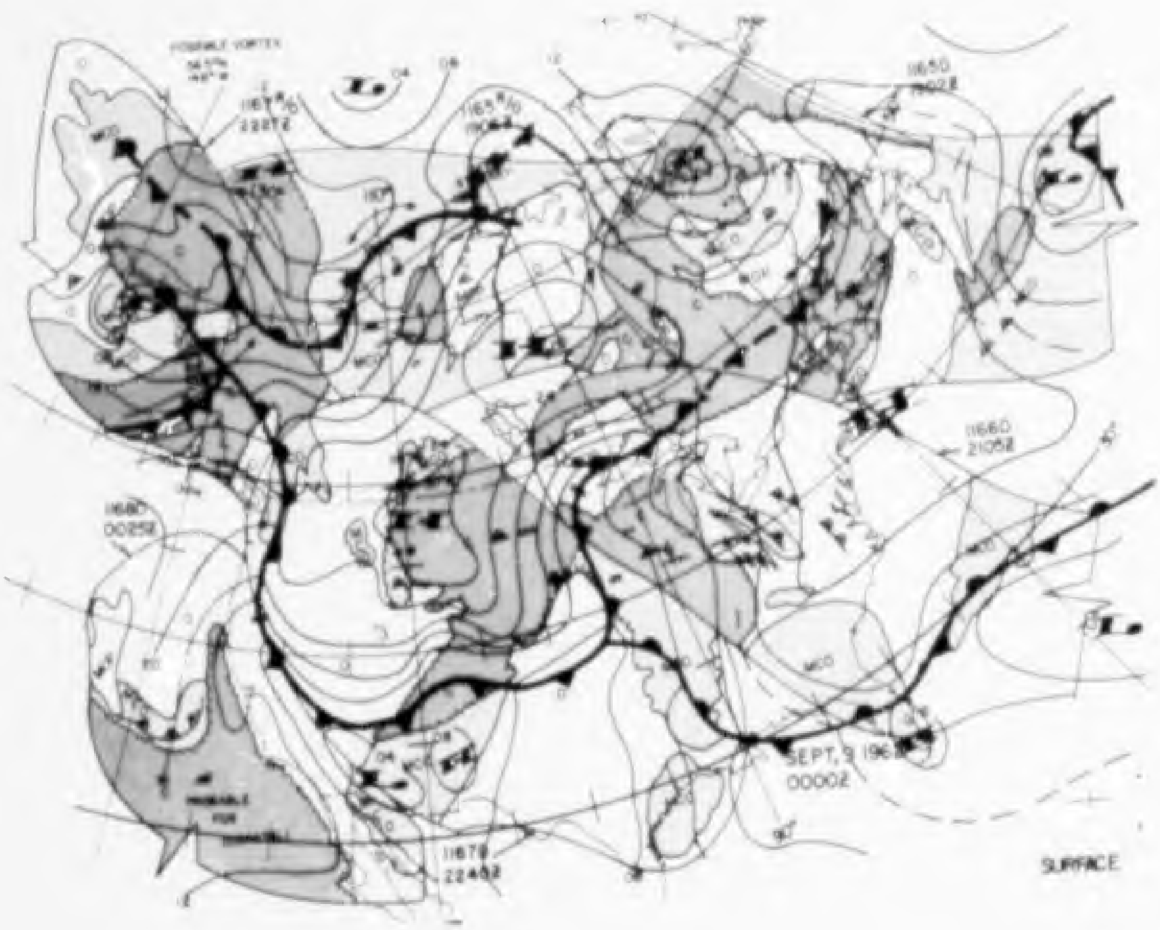


Fig 10-4 Neph Mosaic and Conventional Analyses for 1200Z, 8 September 1962



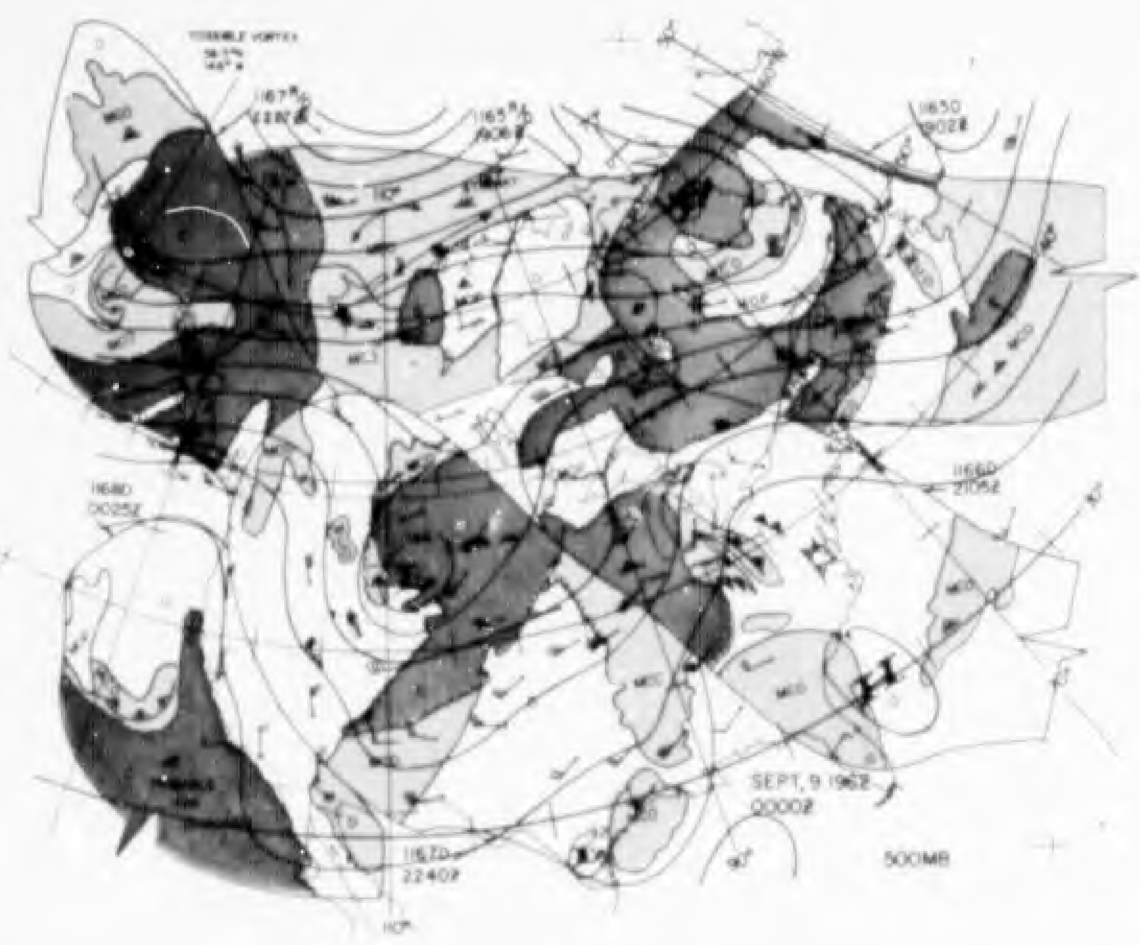


Fig. 10-5 Neph Mosaic and Conventional Analyses for 0000Z, 9 September 1962

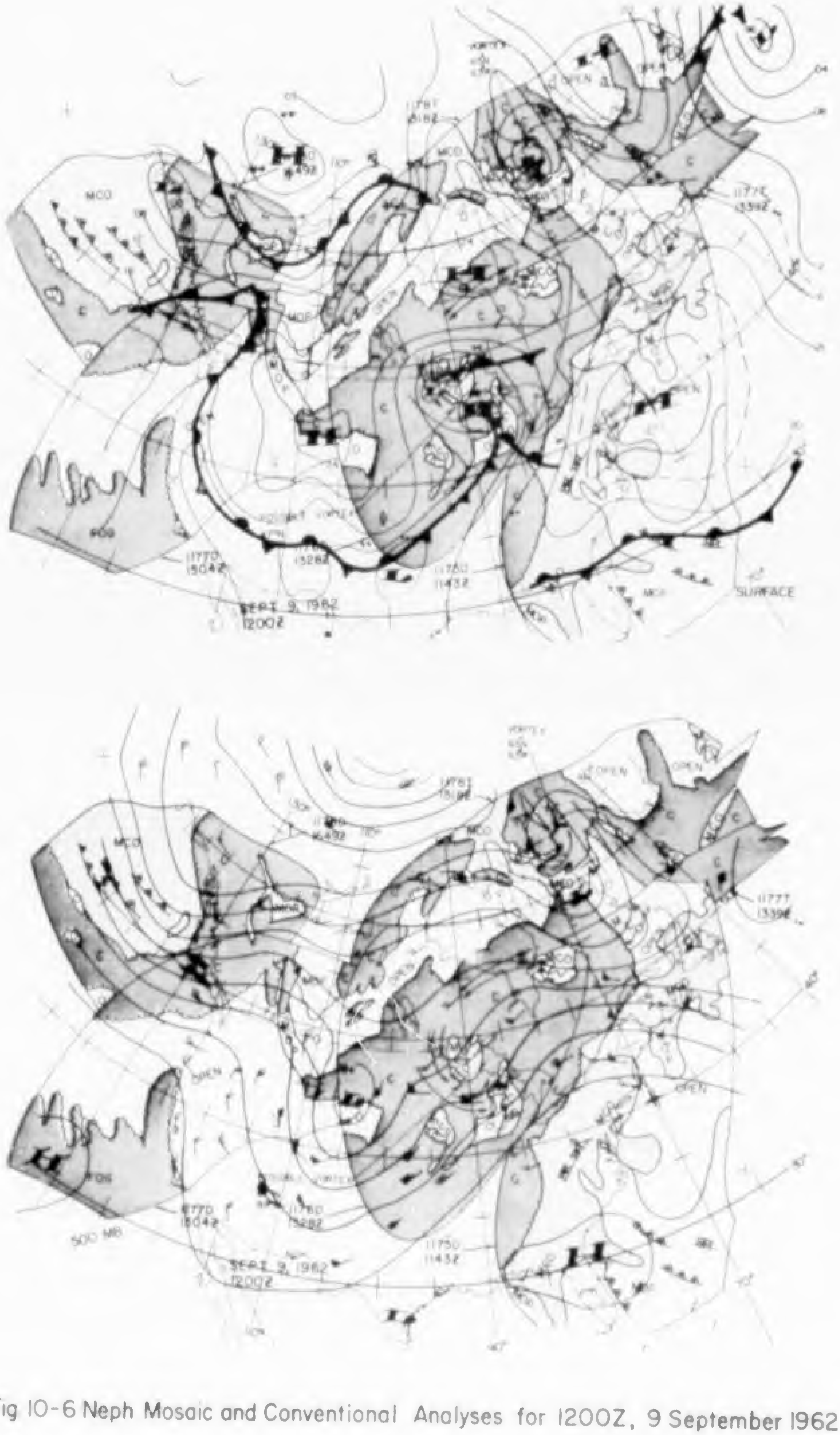


Fig 10-6 Neph Mosaic and Conventional Analyses for 1200Z, 9 September 1962

spread precipitation has now broken out and covers a large part of the Central U. S. The westward boundary of this precipitation could be better deduced from the movement of the rear boundary of the cloud mass than from frontal positions.

Figure 10-9 shows the continued development of the storm which now has the 500 mb and vortex center at 45N, 95W. The precipitation is confined mostly to the area north and northeast of the center in the areas depicted on the neph as heavy covered and covered. Some evidence of the short wave trough and its associated vorticity maximum can still be seen in the cloud pattern over the Gulf of the St. Lawrence near 47N,60W. Precipitation is still occurring in this area, well in advance of the surface frontal system and indeed in the surface ridge. By 1200Z the next day (11 September'62) the vortex shown in Figure 10-10 was centered at 48N, 80W and looked remarkably like the vortex discussed in paragraph 10. 4. 1. 1. Note the resemblance to Figure 10-1.

10. 4. 1. 3 Other Significant Patterns

Many other significant patterns are recognizable in this set of neph mosaics and it is suggested that the reader may care to look for them.

Some of the more obvious are:

1. The extensive area of stratiform and cumuliform cloudiness off the west coast. The definite boundary of this cloudiness along the coast on 9 September, 00Z, and later suggest coastal fog. The boundaries of this fog are evident and would aid in short range forecasts for this area, as was discussed in Chapter 8.

2. The cloudiness moving onto the west coast of Canada on 8 September at 1200Z. The comma-shaped pattern which is evident by 00Z, 9 September suggests an approaching upper trough with strong advection of cyclonic vorticity, and possibly an associated low level occluding storm. By 1200Z, 9 September the trough is evident, and the typical banded cumuliform cloudiness in the cold air behind the upper level trough line is clearly depicted in the neph.

3. In Figure 10-6 the short wave trough along 105W could be suspected from the cloud pattern even in the absence of radiosonde data.

4. The lines of cumulonimbus along the Gulf Coast from Florida to eastern Texas on 7 and 8 September are easily related to thunderstorm activity for this area, and illustrate the identification of mesoscale convective patterns discussed in Chapter 8.

Fig. 10-7 Picture Mosaic of TIROS V, Orbit 1178 R/O 1177, 9 September 1962, 1520Z (Notable features are: Organization of cloud pattern and clear area revealing the Greenland Icecap)

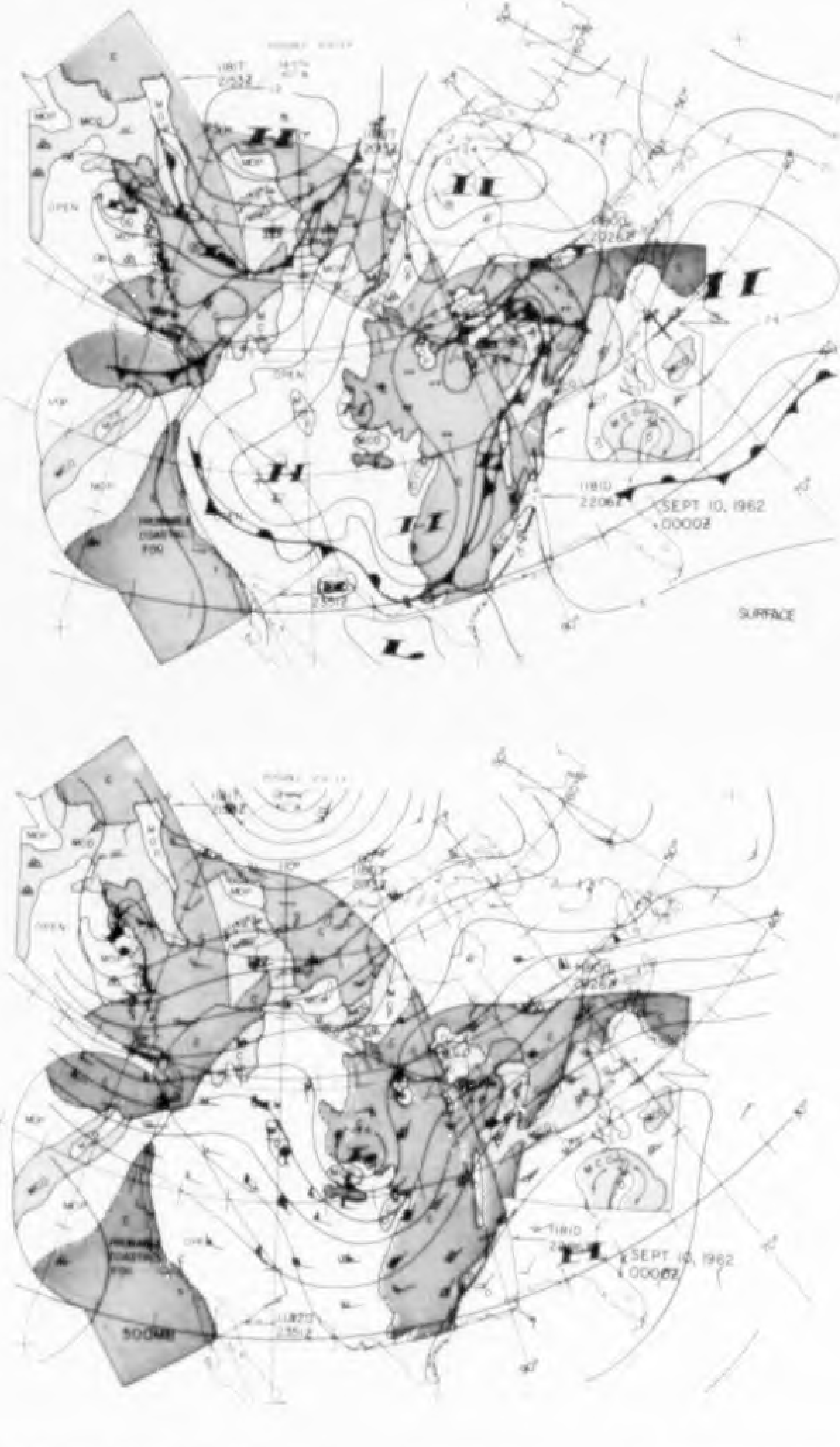


Fig 10-8 Neph Mosaic and Conventional Analyses for 0000Z, 10 September 1962

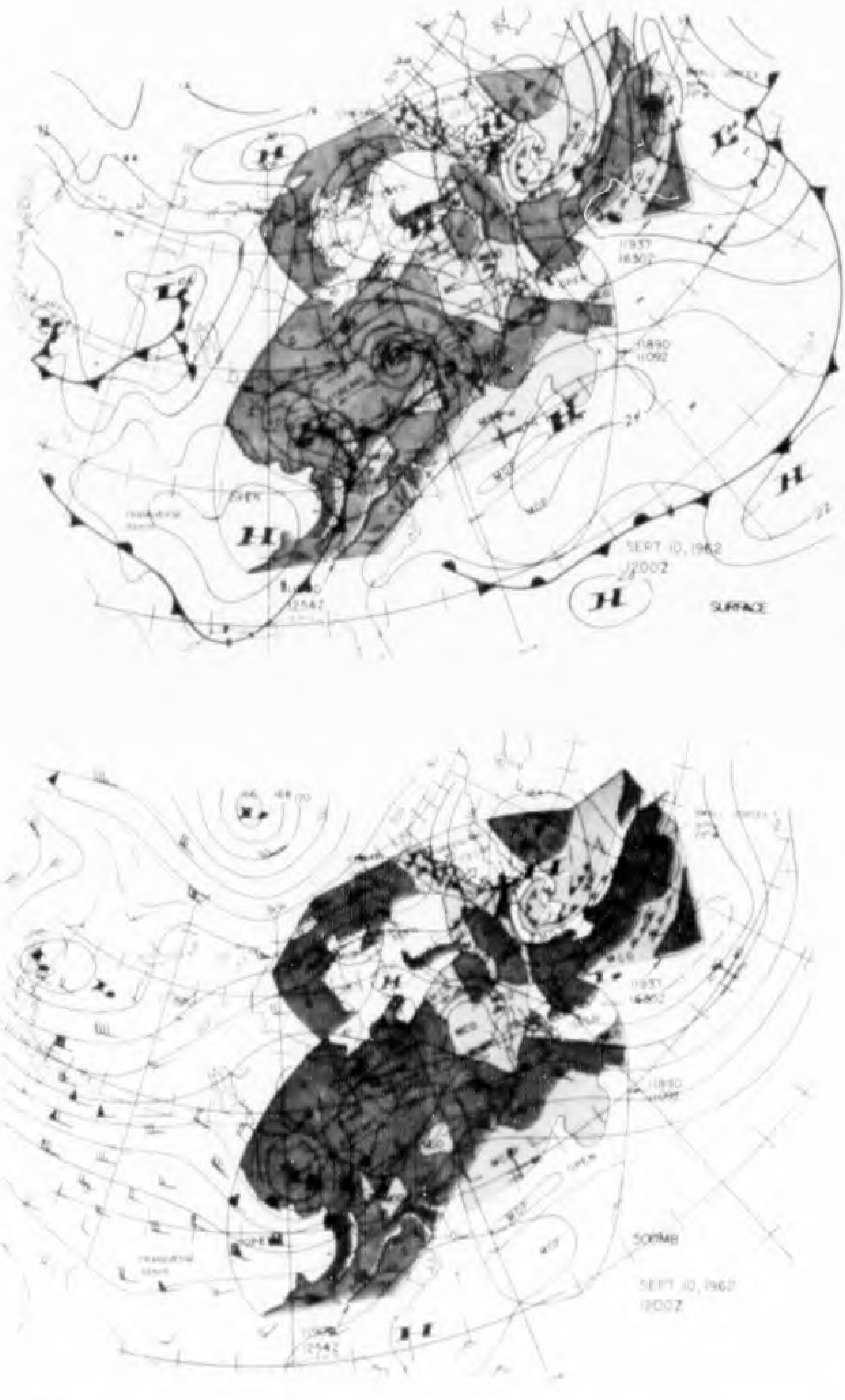


Fig. 10-9 Neph Mosaic and Conventional Analyses for 1200Z, 10 September 1962

Fig. 10-10 Picture of well-developed Vortex from Orbit 1204D, 1220Z, 11 September 1962

10.4.2 A Winter Case

This January 1964 case is based on unmodified operational nephanalyses exactly as they were transmitted over the national facsimile network in the revised notation adopted in early January 1964 and presently in use. The case was chosen for a data sparse area (the North Atlantic). It was chosen at random without specific consideration of the synoptic situation, and only a brief explanation of the synoptic developments will be attempted here.

The particular objective here is to approach, as closely as possible, an actual operational example. Thus the pictures for these orbits were not consulted before or during the basic analysis, and, with a single exception, * discussion results from inferences that were drawn from the nephs alone. This case also illustrates some of the difficulties experienced in coordinating the nephs with the conventional data in those few cases when the cloud patterns (as seen in the nephs without benefit of the pictures) may appear not to correlate well with the conventional data.

Part of this apparent problem resulted from the construction of single neph mosaics for the entire North Atlantic. The neph times over the western part of this area were often closest to the 00Z observations while the neph times for the eastern Atlantic were usually closer to the 12Z conventional data. A better fit might have resulted if the area had been split into two parts, superposing the nearest conventional analysis on each of these parts. The decision whether to use the neph mosaic as a whole or as separate sections should be an operational one, based on the forecast problem at hand. For the purposes of this example, superposition of both the 12Z and the 00Z data will be shown for the first day (27 January 1964). On succeeding days only the 12Z analysis will be shown, thus duplicating a situation where treatment of the entire Atlantic as a single unit seemed desirable.

10.4.2.1 Banded Clouds Southeast of Newfoundland

The neph for orbit 3288/3287** (Fig. 10-11) shows a double cloud band running nearly north-south. One band is along 50W while the second is more or less along 53W. These bands merge near 40-45N and 50W. Juxtapositioning of the neph for

* The last paragraph under the discussions of Figures 10-11 and 10-12, 27 January 1964, in Section 10.4.2.1.

** Data taken on orbit 3287 and readout on orbit 3288.

orbit 3287/3286 adjacent to that for 3288/3287 helps to show an apparent continuation of the bands toward the northeast, generally along a line from 48N, 50W to 57N, 35W. This band and the western portion of the southern band (along 53W in orbit 3288/3287) seem to be associated with the region of upward vertical motion related to an upper air trough and a surface front. The upper level trough is rotating around a low center (located off the figure near 52N, 70W) and moves from a line from 50N, 70W to 35N, 60W at 1200Z, 27 January (Fig. 10-11) to a line from 52N, 65W to 40N, 52W (Fig. 10-12).

The cloud band along 50W (Fig. 10-11) may be a prefrontal band, or it may be partly related to the low pressure system to the south. This system to the south, centered near 28N, 48W, is positioned on 27 January by meager data at the surface and very meager data at 500 mb. A forecaster responsible for this area might be somewhat in doubt as to the actual intensity and location of this system. Although the cloud patterns do not conclusively place the center farther to the east, they strongly suggest that some form of circulation is occurring near 25N, 40W and that the area of strongest vertical motion is east and north of this apparent circulation.

The crescent shaped pattern running generally from 15W, 38N, to 40W and 55N has no obvious interpretation in terms of the conventional data as analyzed for both the surface and 500 mb. An analyst in the field might well have a problem in trying to integrate the satellite and conventional data in this situation. Two or three alternatives could be considered. One would be the conventional analysis being badly in error. In spite of only limited data, it is reasonably certain that a high pressure area exists both at the surface and 500 mb in the area where the neph depicts the "covered" solid cloud area. A second might be that the neph misrepresents what the pictures show. Although this does not often happen, in some few cases the nephs are not drawn or analyzed as carefully as they might be. A third and obviously preferable alternative is to resolve the apparent differences between the neph depiction and the pattern expected from the conventional data. For example in this case, it seems very probable that the "solid" cloud mass actually does lie across a high pressure area at both the surface and at 500 mb. The positions of both centers could be slightly in error, but there is little doubt from the conventional data that they do exist. The anticyclonic curvature of the contours would seem to make an area of extensive middle cloudiness unlikely. The "solid" covered area might be heavy cirriform cloudiness, but with the high extending from the surface through 500 mb, it seems unlikely a flow pattern at cirrus levels appropriate to the cloud configuration would exist.

A second possibility is low level stratiform cloudiness or even sea fog. Here the synoptic climatology for this area (see Section 10.5.2) was found to be helpful. The low level winds around the indicated high pressure area would be bringing relatively warm moist air northward. Cooling by the relatively cold ocean at high latitudes often produces low level stratiform clouds or fog in this area (mid north Atlantic) in winter. Thus, for this case, it seems reasonable to deduce that the crescent shaped pattern and perhaps the mostly covered area along 33W between 40 and 50°N might be low level stratiform cloudiness.

After this case was analyzed and the text prepared, the pictures for this orbit (3287/3286) were examined to determine the validity of this deduction. It appeared that the cloud patterns in the pictures were inadequately depicted in the neph, especially the crescent shaped part. The north-south oriented portion of what was depicted as a continuous crescent is a different cloud mass from that which runs generally east-west. The north-south portion is very flat in appearance, tending to confirm the suspected existence of low level stratiform. The east-west portion had more definition and might be an extension of the cold front shown by the surface analysis to end near 42N,24W. This illustrates a type of problem that the field forecaster must at times contend with in using nephs.

Figure 10-13 presents the 1200Z analysis for 28 January superposed on the neph mosaic. The cloud pattern in the area between Labrador and Greenland has now become more organized and correlates well with the upper air and surface analyses. One might assume that the pattern is now a large portion of the familiar "hooked shaped" pattern associated with a non-closed system at 500 mb. The position of the jet and the band indicated as "frontal" also tend to confirm this assumption. The large cloud "blob" centered in the nearly vertical high pressure area is (like the day before) difficult to explain. However, on this day (28 Jan.) the symbols for cumuliform, stratiform and cirriform appear in the cloud pattern and experience suggests that where this combination of symbols appear on the neph the cloudiness is probably relatively flat in appearance with some texture. The best probable deduction is that low level stratiform cloudiness covers this area.

By 1200Z, 29 January (Fig. 10-14), a short wave pattern is apparent in the 500-mb circulation pattern along a line from about 55N, 33W to 48N, 35W. The trough is clearly in evidence from the winds between ocean ship "Charlie" (54N, 35W) and "Juno" (53N, 20W). This trough and its associated cloud pattern are undoubtedly the same as those indicated in Figure 10-13 by the cloud pattern between Labrador and Greenland and extending to the Southeast. As the analyst gains experience in relating cloud patterns to conventional synoptic data, the "breaks" indicated in the "covered area" near 51N, 43W might be presumed to indicate some form of separation between the cloud mass to the east and that to the west. In this case, it might be expected that the covered area to the east of the breaks is associated primarily with the short wave while the covered area to the west is probably associated with another short wave moving off the coast of Labrador. Since the writer has not seen the pictures from which these nephs were derived, this discussion is based only on what might be implied from the nephanalysis as in a true operational situation.

The area of "heavy covered" centered near 40N, 48W suggests that the upper trough (along 43N, 60W to 33N, 55W) has an area of strong vertical motion associated with it and that the trough line is probably still to the southwest of this cloud area. The cloud pattern also suggests that this short wave trough is probably more intense than depicted in the 500-mb analysis.

10.4.2.2 Cloud Patterns Over Eastern Europe

The cloud pattern shown on the neph mosaic in Figure 10-11 indicates a complicated synoptic pattern over Europe. No nephs for the previous day were available, so satellite continuity for this area is not possible. The cloud patterns seem to correlate reasonably well with both the surface and the 500-mb conventional data but the discussion here will be limited to the following two days when a continuity of patterns can be used.

By the next day (Fig. 10-13) the cloud pattern indicated as "mostly covered" over the British Isles and the "covered" band across the Low Countries and France mark the position of the upper trough and perhaps the surface frontal position. If the front is associated with this band, it has moved approximately 17° of longitude in 24 hours at 50N, a velocity of greater than 25 knots. If this is the case, the front is almost certainly not washing out as indicated on the surface analysis.

The indication of a circulation center at 53N,12E suggests a short wave trough in the upper flow. Although the surface analysis does not extend that far east in this area, there is no evidence of any low level circulation in the surface data. Furthermore, the covered area extending from 50N to 60N between 10W and 16W, indicated as stratiform, does not fit the conventional surface or 500-mb data. It does however suggest some sort of disturbance moving through this area (such as a short wave

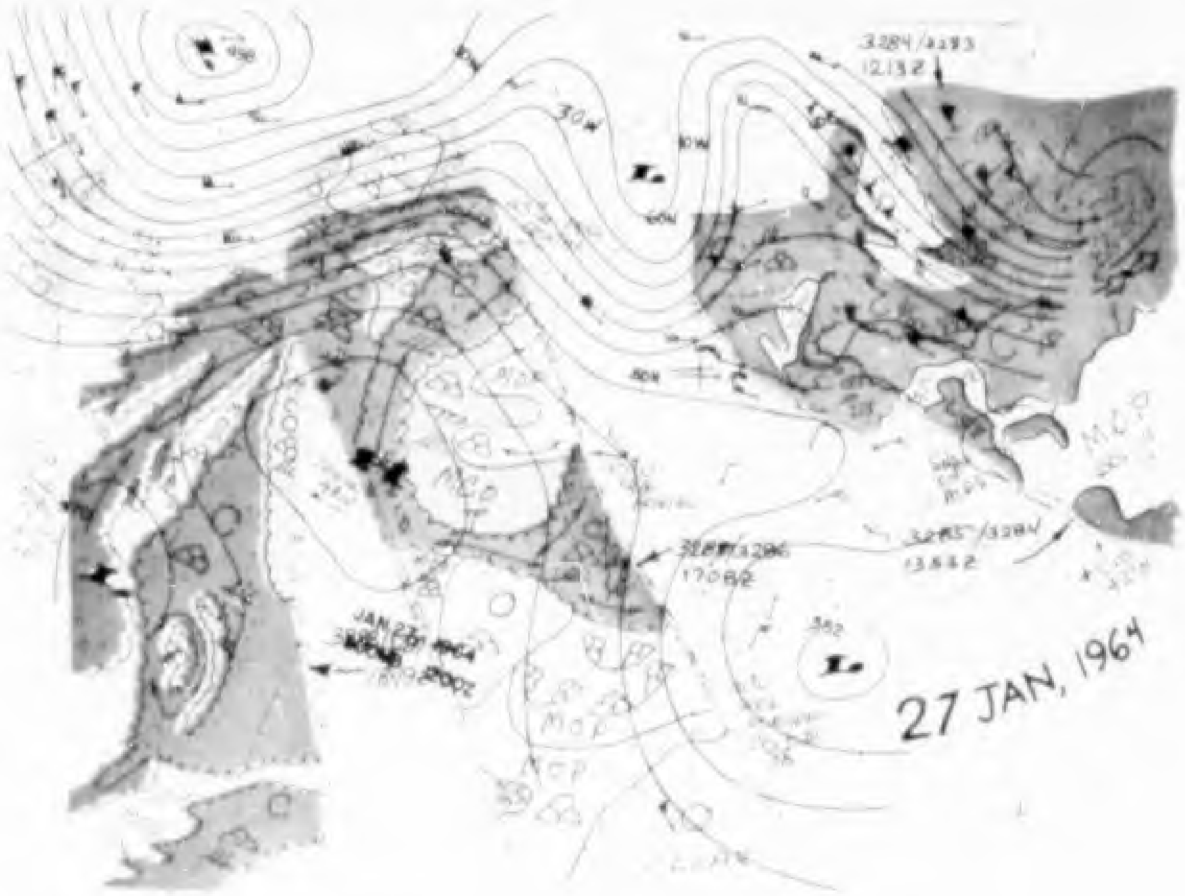


Fig. 10-11 Neph Mosaic (TIROS VII) and Conventional Analyses for 1200Z, 27 January 1964

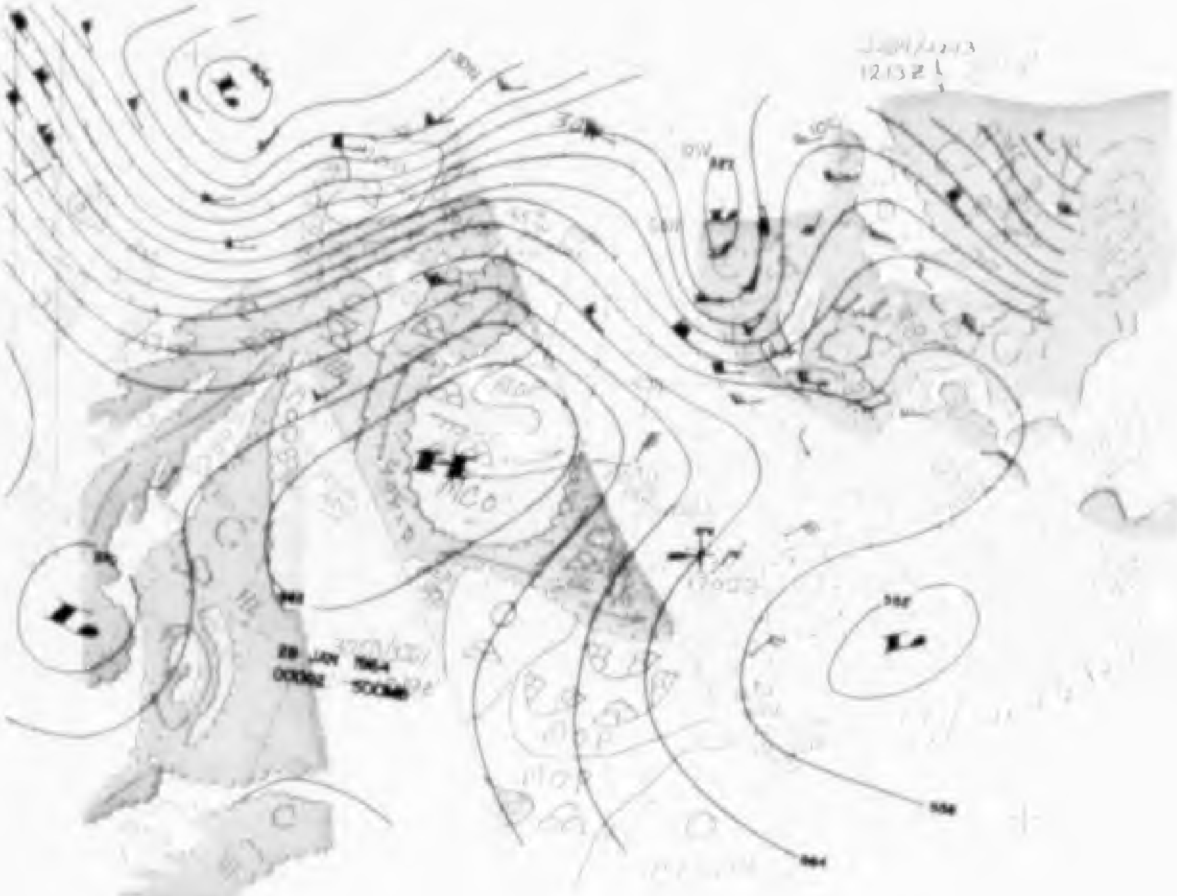


Fig. 10-12 Neph Mosaic and 500-mb Conventional Analysis for 0000Z, 28 January 1964

aloft) which could give rise to moderately strong vertical motion and result in middle clouds as indicated.*

By 1200Z,29 January (Fig. 10-14), a very large covered area appears over the North Sea and the Scandinavian Penninsula. This large area may be low cloud, but the presence of middle clouds the day before (discussed in the previous paragraph) also suggests that some small disturbance is moving through this area. The nature of this disturbance and its correlation to conventional data are not apparent from the neph, but the fact that a large covered area is present cannot be denied. In such a case, an APT picture might reveal subtle differences in the clouds from one area to another and further aid in the interpretation of the cloud patterns.

10.4.3 A Summer Case

In this case, certain extensive cloud systems (shown in Fig. 10-15 for 15 August 1962) are initially associated with a 500-mb trough and a complex closed system at the surface. By 16 August the related upper level pattern is closed over southern Labrador and a deep occluding system is located north of Newfoundland. A change in the cloud pattern reflecting the development of this storm is easily recognizable. This case, where the conventional data for verificati - are relatively adequate, is shown as another example of the relation of recognizable changes in the cloud patterns to changes in tropospheric flow patterns.

The cloud mass over the eastern United States and Canada will be discussed in detail, while other significant features will be listed in the last paragraph of this section. It will be seen that for this case the cloud patterns fit both the surface and 500-mb levels; the surface fit is probably better than for any of the other cases discussed in this chapter.

10.4.3.1 The Banded Cloud Pattern Over Eastern United States and Canada

The three hour difference in time between the neph for orbit 808D (2117Z) and the analysis time shown in Figure 10-15 (00Z) is inadequate to account for the fact that the cloud pattern seems to lie in or on the west side of the southern portions of the upper level trough.

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* The indication of stratiform clouds on the neph usually is reserved for middle clouds. Low stratiform is normally called out by notes outside the nephed area.

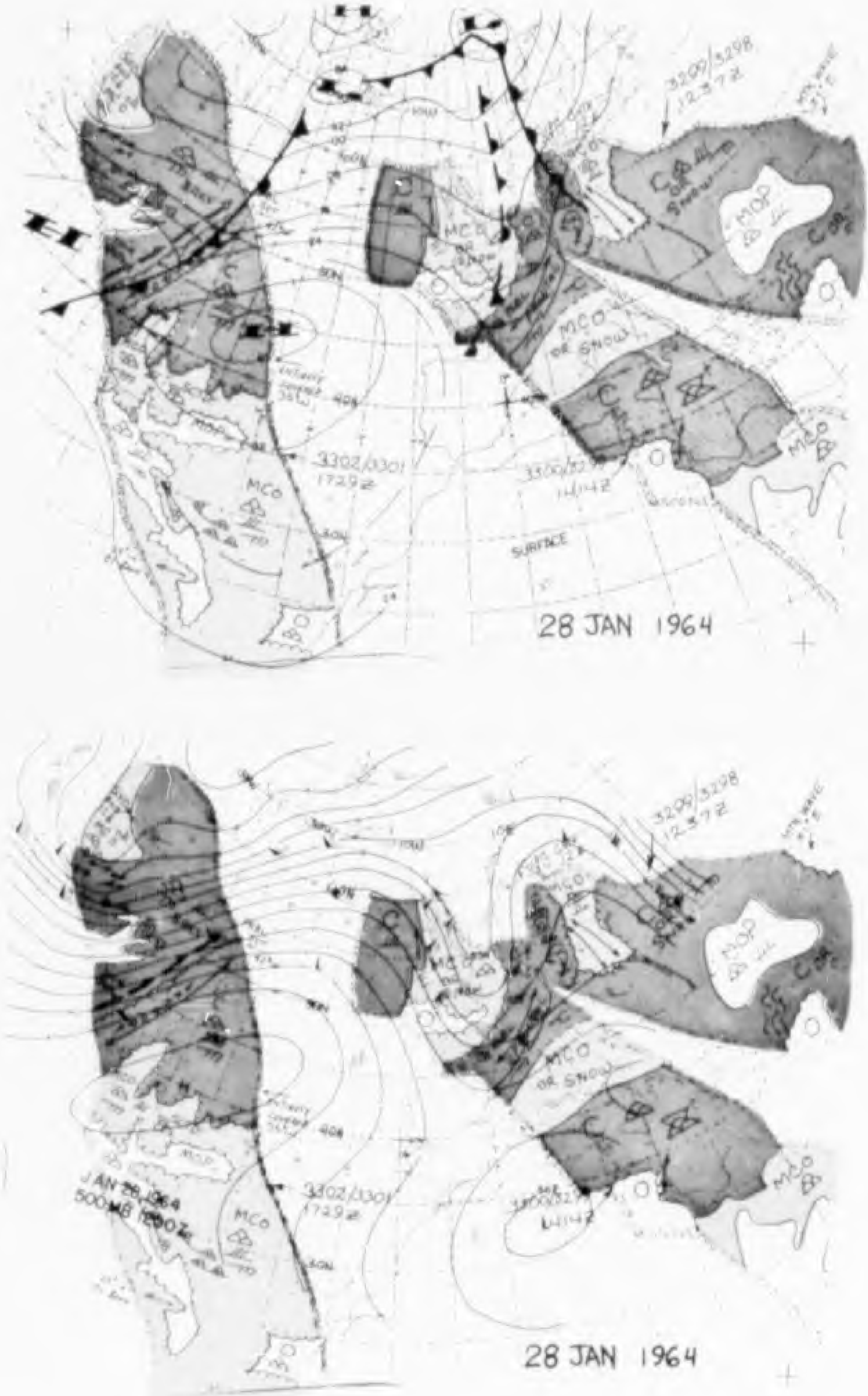


Fig. 10-13 Neph Mosaic and Conventional Analyses for 1200Z, 28 January 1964

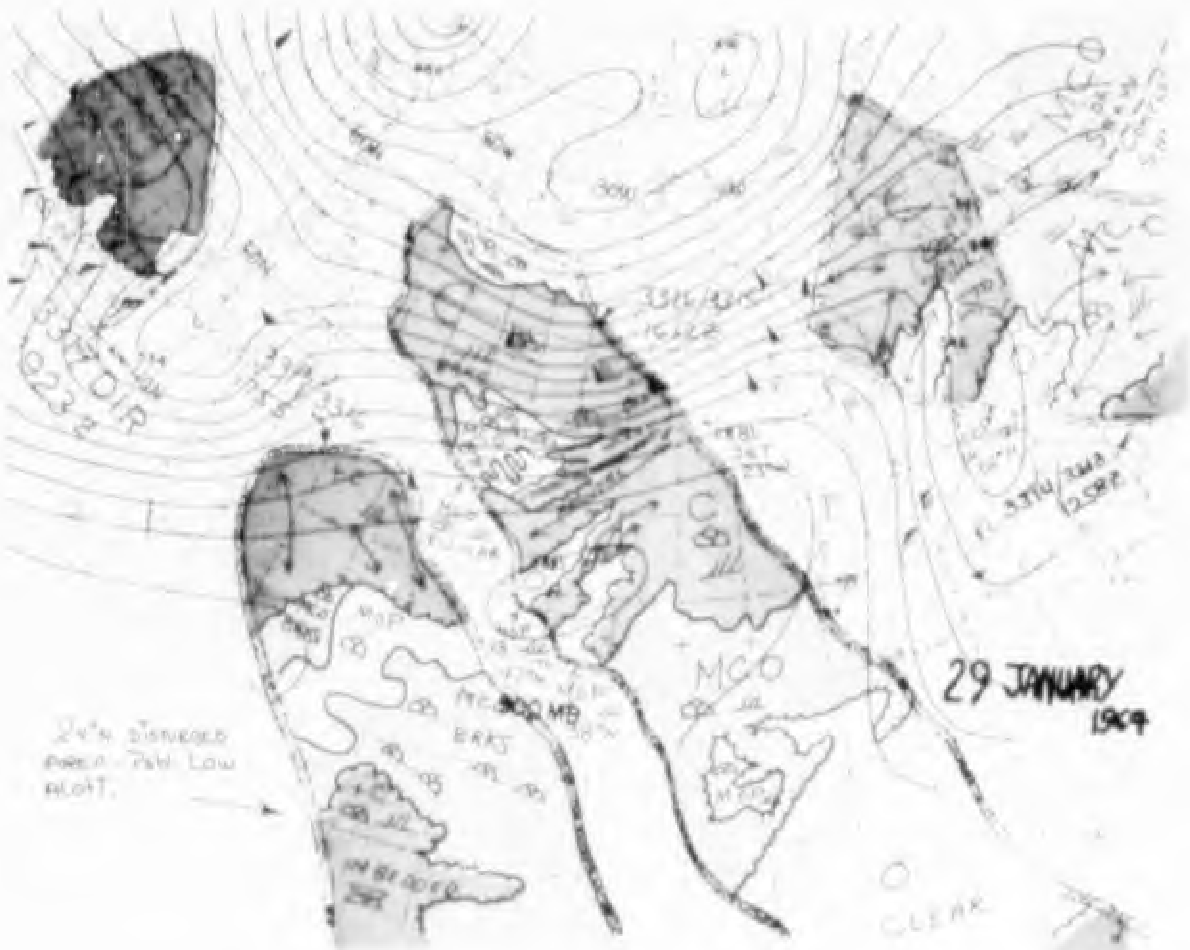


Fig. 10-14 Neph Mosaic and Conventional Analyses for 1200Z, 29 January 1964

A more careful analysis reveals that the covered areas on this neph (heavily shaded) are associated with at least three different areas of upward vertical motion rather than to a single pattern associated with the major trough. The overcast area over Canada and New England, and that over northern Florida and the Georgia coast, seem to be associated with the vertical velocity field resulting from the large amplitude trough at 500 mb. The northern overcast area can also be associated with the surface low and frontal system, while the southern overcast may be in part a prefrontal instability area.

The overcast area over Indiana, Ohio, and western Pennsylvania seems to be a separate mass of cloud which probably results from an unanalyzed short wave in the middle troposphere whose presence is suggested by a careful examination of the plotted wind data. This is an example of a situation where an APT picture might have revealed subtle differences in the cloud, and so have aided in the integration and interpretation of the data. For example, Figure 10-17 shows Frames 3 and 8 from orbit 808D. The very bright cloud east of Lake Huron is definitely separated from the bright cloud mass over Ohio. The cloud mass over Ohio appears flat, indicative of stratiform, while the area east of Lake Huron shows more definition and is probably more cumuliform in nature. A closer examination of the 500-mb winds at Flint, Dayton, and Pittsburgh suggests some form of trough or disturbance in the wind field in this area which was not depicted in the contour analysis. This illustrates a case where the combination of data could have led to a better analysis even over the U. S.

The third area of overcast skies, over central Alabama, Mississippi and Louisiana, is associated with both the 500-mb trough and the surface frontal pattern over this area.

The cloud pattern (on the neph) north and east of Lake Ontario resembles the pattern expected with a surface system just prior to occlusion when no closed circulation at 500 mb exists. By 00Z, 16 August (Fig. 10-16), the cloud pattern indicates an early stage of an occluding frontal system at the surface. The lack of dry air spiraling into the cloud mass and the lack of breaks or streaky appearance in the covered area on the north and west side of the apparent center seem to indicate that the 500-mb trough is not closed <u>at neph time</u>. A tendency toward spiraling can be seen and it would be expected that the 500-mb center is about to close off. Both the frontal pattern and the 500-mb pattern shown in Figure 10-16 support this hypothesis (when the time difference between the neph and 00Z is considered), and indicate the deductions that might be drawn about both surface and upper air contour patterns if such a cloud pattern were observed over a data sparse area.

10.4.3.2 Other Significant Features

Several other significant features can be noted in these nephanalyses, including:

1. The area of coastal fog lying just off California on 15 August.

2. The persistent pattern of the mostly covered area over the mountain states of the US on both days indicates the cloudiness in this area is probably orographic cumuliform cloudiness, as would be expected from climatology for this time of day and year (see Chapter 8).

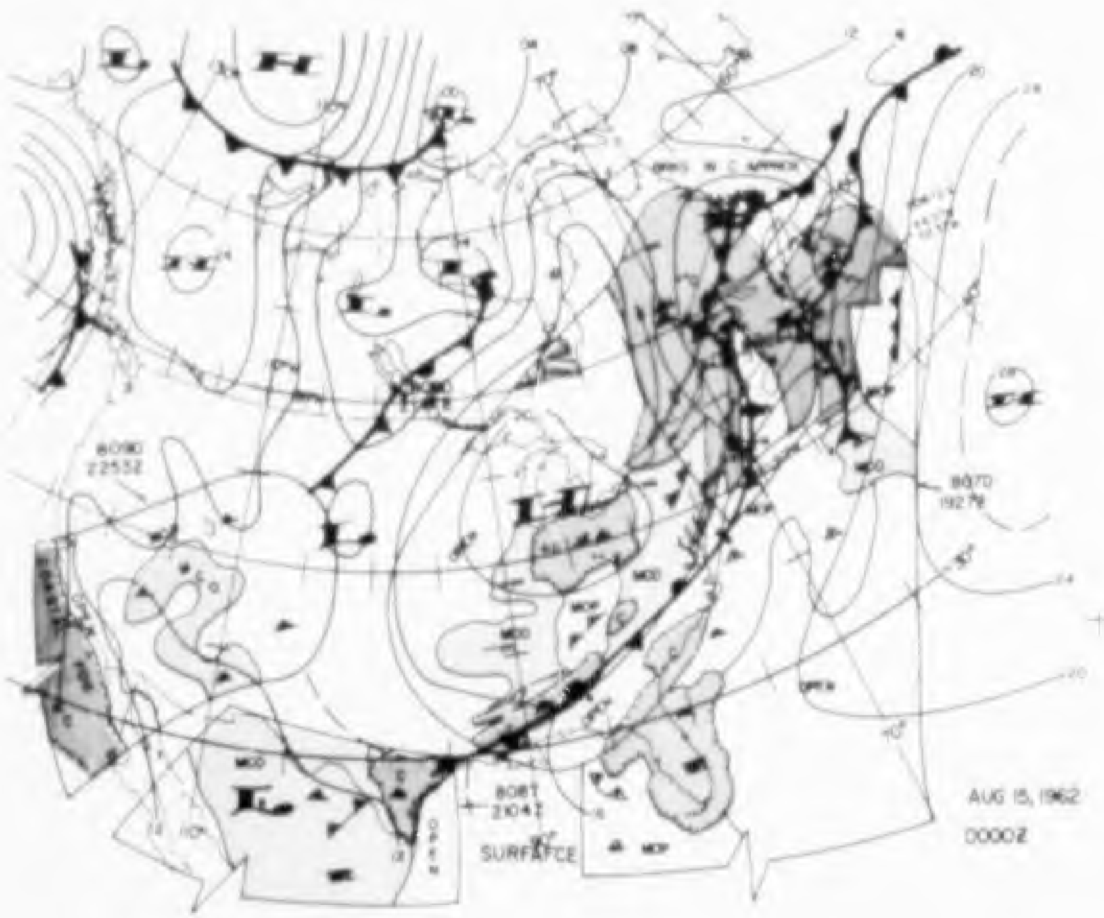
3. On 16 August (Fig. 10-16) a band of overcast skies, preceding the upper level trough which runs along 90W, can be clearly seen and associated with this trough and a surface frontal system. The advancing edge of this cloud system is clearly marked.

10.4.4 <u>A Spring Case</u>

This case, for 19-21 April 1963, was chosen at random and checked for conformance to the criteria stated in Section 10.4. Coverage on the first day is over the central and eastern U. S., Canada, and into the western Atlantic, where relatively good conventional data exist. On 20 and 21 April, the synoptic systems moved over the data sparse Atlantic, where the integration of the nephanalyses and conventional data materially aided in constructing a better synoptic analysis. Cloud patterns related to three synoptic situations will be discussed in some detail.

10.4.4.1 Vortex Pattern Over Minnesota

The composite nephanalysis for 19 April, Figure 10-18, shows a vortex cloud pattern over Minnesota. From the neph, one might estimate that this storm might be at the "beginning of occlusion" stage, as depicted in the models presented in Chapter 6 (Fig. 6-7). Figure 10-19 is a tape mode frame readout on orbit 4363. Except for the orientation of the frontal band, this case, including the upper level trough position and flow pattern, fit the Chapter 6 example very well. The neph time for this particular orbit is closer to the 00Z analysis time, but has been included with



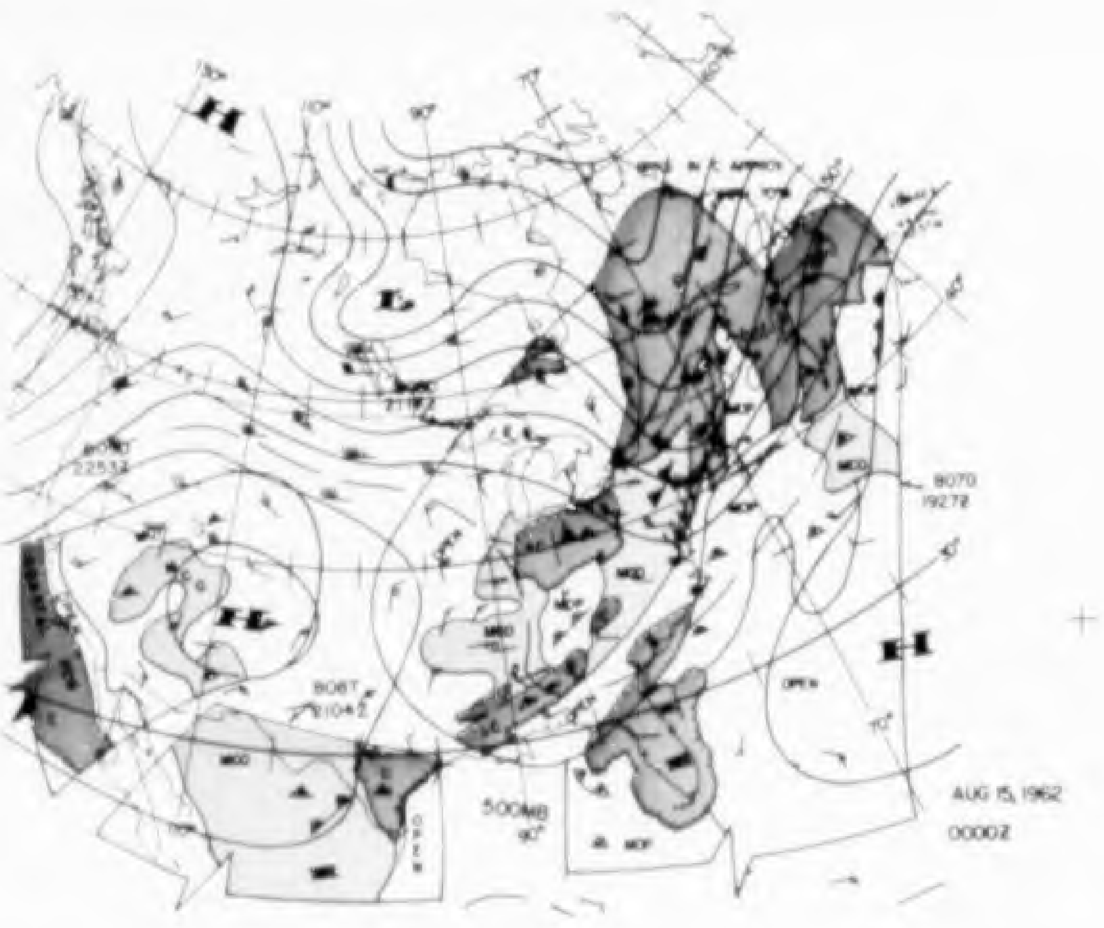


Fig. 10-15 Neph Mosaic and Conventional Analyses for 0000Z, 15 August 1962

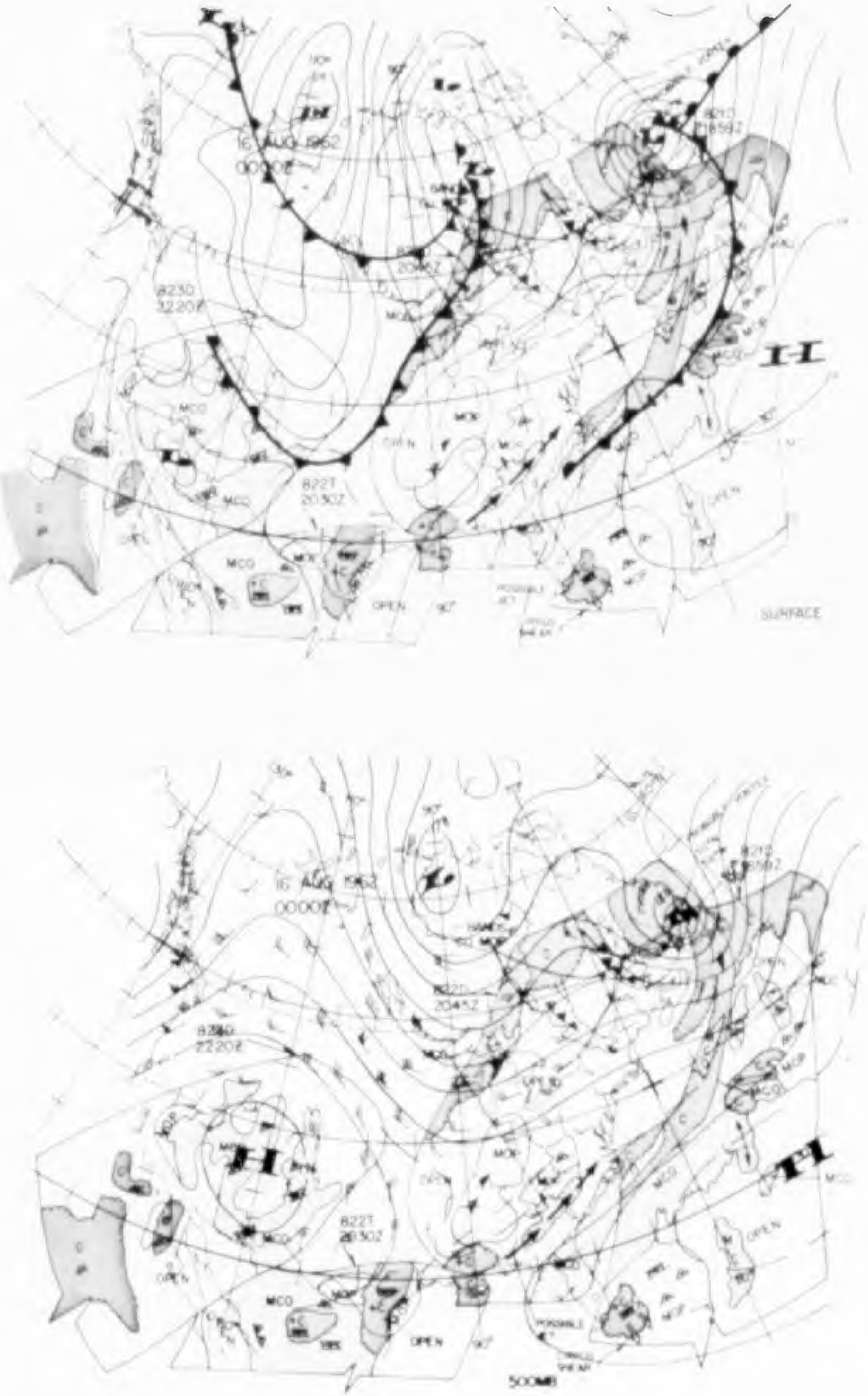


Fig. 10-16 Neph Mosaic and Conventional Analyses for 0000Z, 16 August 1962

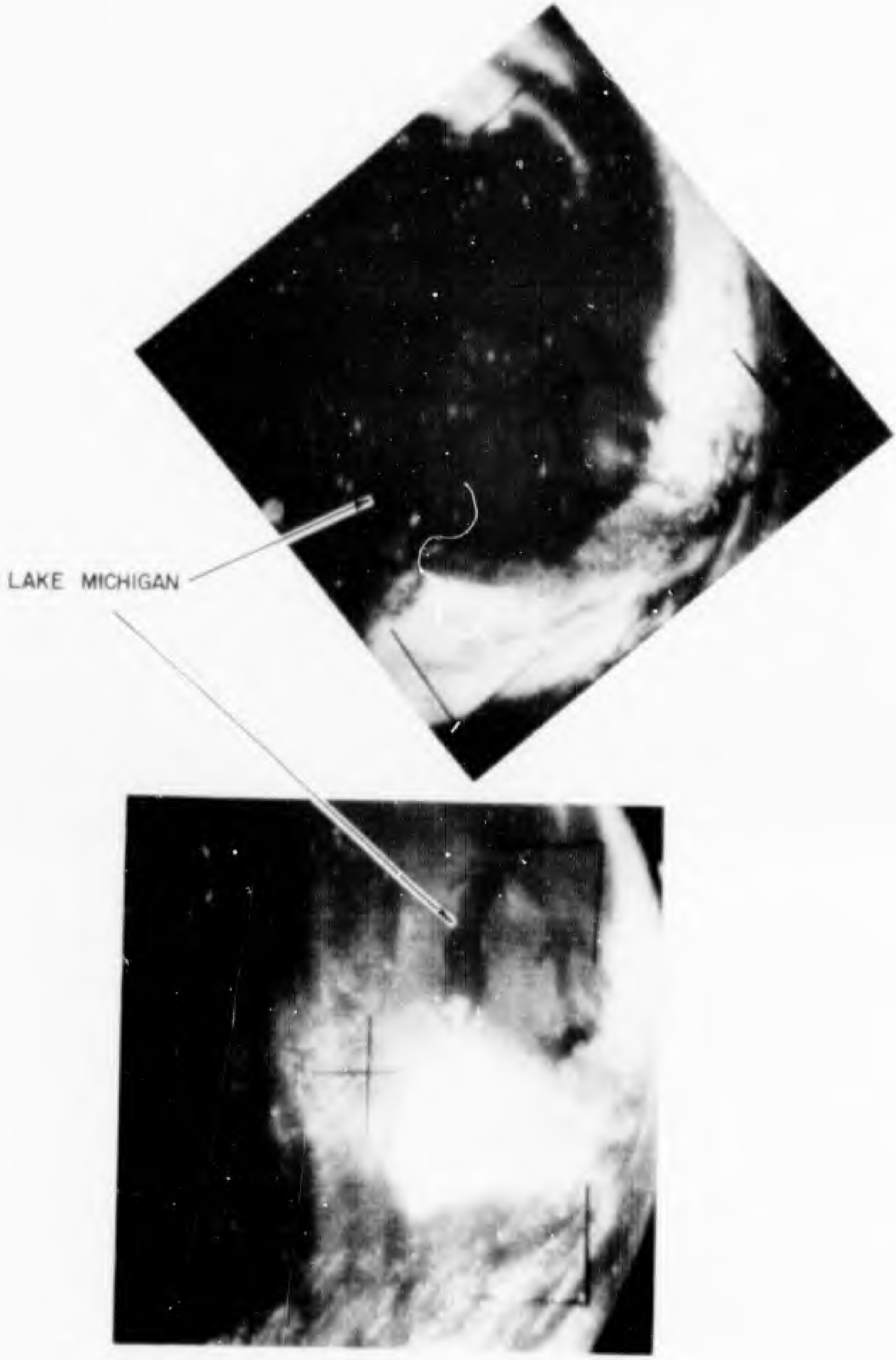


Fig. 10-17 Pictures from Orbit 808D Showing Cloud Patterns Near the Great Lakes. (Note the cloud mass over Ohio has flatter appearance than the cloud mass east of Lake Huron.)

the other orbits (which are closer to 1200Z) for the purposes of continuity of coverage over the area under discussion. The same neph, with the 00Z surface data superposed, is shown above the picture in Figure 10-19.

The vortex over Minnesota can be seen (Fig. 10-18) to be associated with a low pressure system with a vertical axis. The compositing of the nephs allows the eastern boundary of this system to be clearly depicted and the frontal band to be readily recognized. This band suggests that the frontal system at about 1800Z (near the neph time) should be nearly as far east as it is analyzed to be on the 00Z surface analysis (Fig. 10-19). A forecaster finding this pattern over a data sparse area could use the position of fronts and the upper level trough relative to the cloud pattern, as shown in Chapter 6, Figure 6-7, to establish anchor points for both surface and middle tropospheric synoptic analyses.

This system also illustrates the concept that when a frontal band extends well equatorward of the vortex center, an abrupt ending or a splitting of the band usually indicates the position of the upper level trough line (see Section 6.8.2). In Figure 10-18, the frontal band extending across Mississippi, Louisiana, and Texas is split near Huston. Considering the time difference between the neph (1925Z) and the 500-mb analysis (1200Z), this splitting coincides with the upper trough position. The same inference can be made from the neph for the next day (Fig. 10-20). Here the same frontal band now extends from 40N, 63W across Georgia, Alabama, Mississippi, Louisiana, and into Texas. The band is depicted as covered or mostly covered, except for an open area just east of South Carolina which coincides with the position of the upper air trough.

The satellite did not acquire pictures over the main closed system, which is still reasonably vertical. Based on the conventional data, the 500-mb center north of Lake Superior is west of the surface center over James Bay. The cloud mass indicated on the 20 April neph as a "possible vortex" at 44N, 75W over Vermont is the now weakened remnants of the center which was in the trough over Minnesota 24 hours earlier. Heavy cloud cover can be seen near the 500-mb ridge line which runs north-south along 65W. It probably results from vorticity advection associated with the 500-mb trough line from James Bay to Pennsylvania. This trough has moved eastward at nearly 50 knots; thus the four hour difference between neph and analysis time would account for the area of <u>heavy</u> covered cloudiness (+C) appearing to extend across the 500-mb ridge line over New Brunswick. The distinction between the <u>heavy</u> covered area and the perhaps less significant areas of broken and covered cloudiness to the east, as depicted on the neph, is clearly visible in the TIROS pictures (Fig. 10-22) upon which the neph was based. The surface frontal analysis shown in Figure 10-20 is also four hours earlier than the neph, but even taking this into account the cloud pattern suggests the northern portion of the cold front and the point of occlusion probably should be positioned further east or northeast by at least 5° of longitude.

The cloudiness over eastern Canada merges with that associated with another storm to the east, which has moved from eastern Quebec and is over Newfoundland by 1200Z, 20 April. The cloud outline to the southeast of Newfoundland suggests a well defined trough extending south of the center. Still farther to the southeast, near 44N, 44W, another cloudy area is associated with the southern extension of this trough. This pattern will be discussed in detail in a later paragraph.

During the next 24 hours, the cloud pattern southeast of Newfoundland becomes more organized and a vortex is indicated on the neph (Fig. 10-21) at 47N, 51.5W. The clear area south of New Brunswick, coupled with the 500 mb wind shifts at Nantucket and Caribou, indicate that a trough has passed this area in the last 24 hours. Clear skies now indicate the presence of a ridge. The trough, which moved past Nantucket, moved into the area west of the system which at 1200Z, 20 April was centered over Newfoundland. The neph for 21 April (Fig. 10-21) indicates the increased organization of the pattern, and a probable increased intensity of the storm.

The cloud pattern at 1600Z would seem to indicate that the surface pattern might be in a more fully occluded stage than indicated on the surface analysis, with the cold front extending along the cloud band indicated on the neph from 40N, 45W to 35N, 50W. This would place the front nearly 10° further east at 40N. The surface data would easily allow the fronts to be reanalyzed to better fit the cloud pattern. Such an improved analysis should aid in future forecasts for this area. With the organization shown in this cloud pattern, a forecaster might reasonably forecast the closing off of a 500-mb center near 50N in the very near future, and the possible further occluding of the surface storm.

10.4.4.2 Small System in the Mid-Atlantic

On Figure 10-18, a small "blob" of heavy cloud is apparent in the mid-Atlantic Ocean near 30N, 50W. The shape and size of this cloud mass suggests a short wave trough at mid tropospheric levels, with or without a related developing surface system. An analyst seeing this type of cloud pattern should suspect a wave in the

500-mb contour field and a possible development of a surface system nearly under the cloud form. In this case, a suggestion of an upper level trough is apparent in the 500-mb contour pattern along 57W between 36 and 41N. The cloud pattern in this case suggests that this short wave trough is not the same trough that appears to begin at 44N and run between Nova Scotia and Newfoundland into the low pressure area over eastern Quebec. By 1200Z, 20 April (Fig. 10-20) the trough which was more or less along 63W on 19 April has moved to 52W and has been analyzed as extending southward to 30N along 50W. The neph shows a "hooked" - or "comma" - shaped cloud mass along 45W between 40 and 45N. The location and shape of this cloud mass indicate that the short wave along 57W, 24 hours before,has moved to 47W. Using this information, an analyst might tend to draw less of a sharpening and southward extension of the western most trough along 50W, and instead to place a short wave trough near 40N, 45W. After such a reanalysis, a forecaster might have a better indication of the events to take place in the eastern Atlantic during the next 24 hours.

The surface analysis near 40N, 45W shows a frontal system with a small occlusion. Even after taking the two and one half hour time difference into account, the cloud pattern would still indicate that the position of this low level system should be at least 5° further east and 4° to 5° further north. A close examination of the surface map for 1200Z shows no data that would prohibit such a reanalysis. Thus, it seems reasonable to assume that the system is more likely to be where the cloud pattern indicates than where the NMC analyst placed it based on sparse conventional data alone.

By 1450, 21 April (Fig. 10-21) the cloud pattern near 45N, 27W has the "comma" shape which was described in Chapter 6 and was shown to be associated with the combination of vorticity and thermal advection downwind of an open wave pattern at the 500-mb level. Recognition of this pattern often allows 500-mb contour patterns to be estimated with some precision over data sparse areas. In this case the trough is verified by the data from ocean ship "Delta" (45N, 41W) and Lages in the Azores (38N, 27W). The associated surface system should be centered near 45N, 26W, with the cold front along the cloud band shown in the neph; the surface analysis for this area as shown in Figure 10-21 seems to be misplaced. A careful examination of the surface data indicated no data which would be violated if the system were moved to fit the cloud pattern. Thus again the cloud pattern coupled with the conventional data led to a better analysis. In this case, the surface system would be moved some 250 or more miles closer to the coast of Spain and would materially affect the forecast for that area in the subsequent period. Any weather associated with this system might now be expected to arrive over northwestern Spain during the next 12 hours whereas from the frontal positions as analyzed, associated weather would probably not be expected for nearly 24 hours.

10.4.4.3 The Double "Vortex" Pattern Over the Central North Atlantic

A double "Vortex" pattern in the North Atlantic can be clearly seen in Figure 10-18. The cloud system centered near 50N, 39W has the appearance of being closed at 500 mb, and shows a heavy band to the northwest of the center. As discussed in Section 6.6.2.1, this type pattern usually occurs with cyclonic curvature of the 500-mb contour field in the area of the heavy cloudiness. This is a good example of this feature and indicates how an analyst might construct the contours near such a cloud pattern if little or no other data were available.

The eastern system centered near 44N, 26W does not have the appearance of a closed upper level system, but the bands in the cumuliform cloudiness of the "mostly covered" area indicated in the neph suggest that the system may be closed at the surface. Thus one would suspect an upper level trough with an associated closed surface system. The meager conventional data in this area seem to verify this. The cloud pattern suggests that the northern end of the front, shown as disconnected from the low level center, might be extended to the northwest and somewhat "wound up" to a more hooked shape. Again, the available conventional data would not contradict such an analysis.

By 1200Z, 20 April (Fig. 10-20), the upper level center has drifted southeastward from 52N, 36W to 49N, 27W. The cloud patterns shown in the neph for 1254Z, 20 April suggest that the upper level flow favors intensification of the new closed center that developed from the trough which was near 44N, 26W a day earlier and is now near 52N, 12W. The old circulation center is still apparent but is now depicted to contain only broken clouds. The new system seems to have some organization, but it would be difficult to recognize without the aid of the conventional data.

Figure 10-21 shows that this new system had considerable organization by 1200Z, 21 April; it now looks like a vortex in the fully occluded stage. A closed circulation extending from the surface through 500-mb is highly probable, and the axis of the system is likely to be nearly vertical. The conventional data support this conclusion. The implications of this type of analysis for data sparse areas are obvious.

10.4.4.4 Some Deductions From This Case

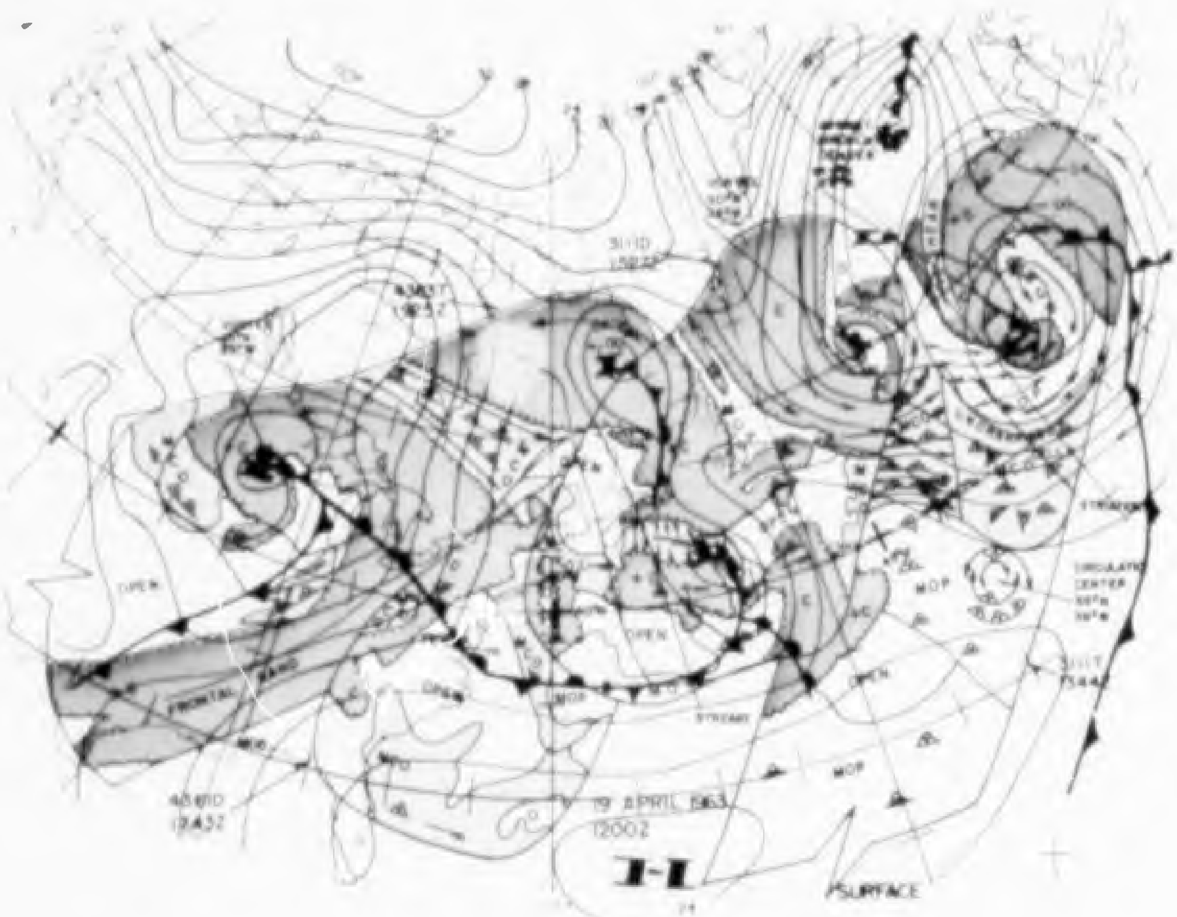
This case has clearly pointed out some of the advantages to be gained from the compositing of nephs and the superposing of conventional analyses. The resultant maps suggested that there were several areas where an improved synoptic analysis could have been made. Time-tested techniques such as continuity, when used to supplement the integrated data, also aided in the positioning of major synoptic patterns and helped to reveal which systems were likely to produce significant weather. Over data sparse areas, such as in this case example, there is no doubt that these procedures can lead to better synoptic analyses and so to significantly improved forecasts.

10.5 FURTHER CONSIDERATIONS IN AREAS OF SPARSE DATA

Where data other than the satellite observations are inadequate, fullest possible use should be made of all other information at the forecaster's disposal, such as climatology, synoptic climatology, physical relationships, current prognostic charts, etc.

10.5.1 Applications of Climatology

For almost all individual areas of the world, and for all seasons in these areas, there are certain weather conditions that are probable and others that are highly unlikely. These facts are normally considered by the careful analyst when making any weather analysis or forecast. Especially when other data are sparse or nonexistent, such knowledge should be applied in basing analyses on the satellite observations. An analysis suggested by the satellite data should obviously be most carefully reviewed if it indicates weather conditions or synoptic patterns that are highly unlikely, climatologically, for that area or season. On the other hand, the fact of climatological reasonableness (while by no means proving the correctness of an analysis) does add confidence to inferences drawn from the satellite data.



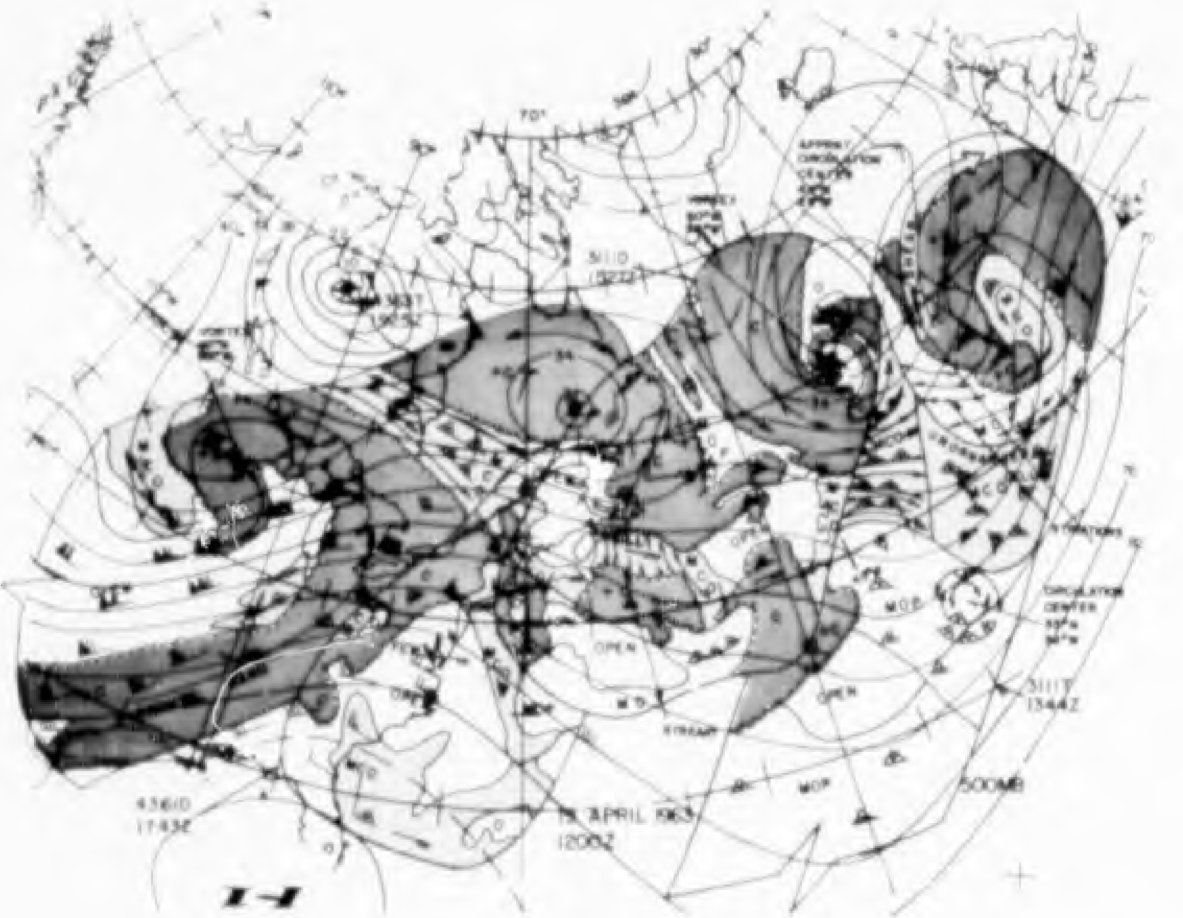


Fig. 10-18 Neph Mosaic and Conventional Analyses for 1200Z, 19 April 1963

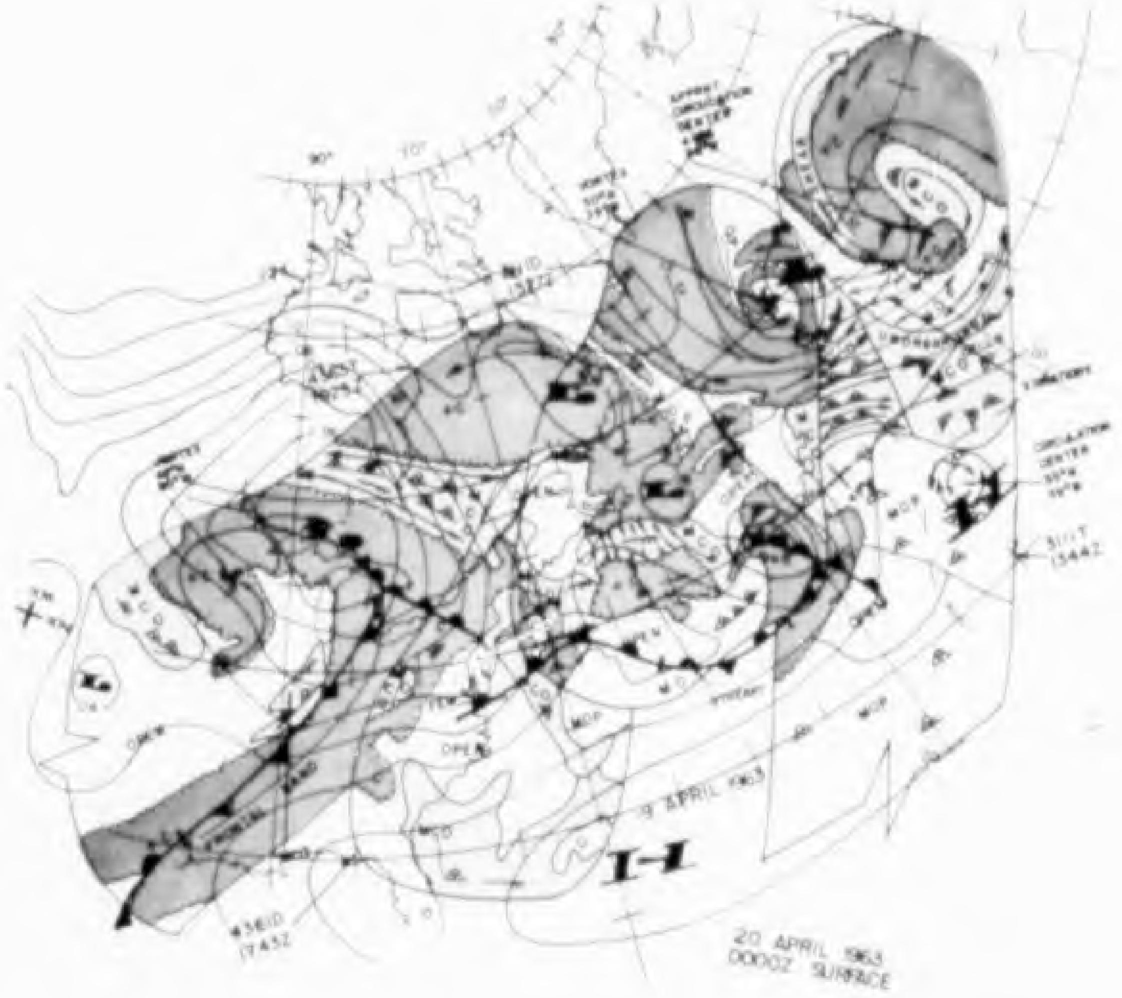
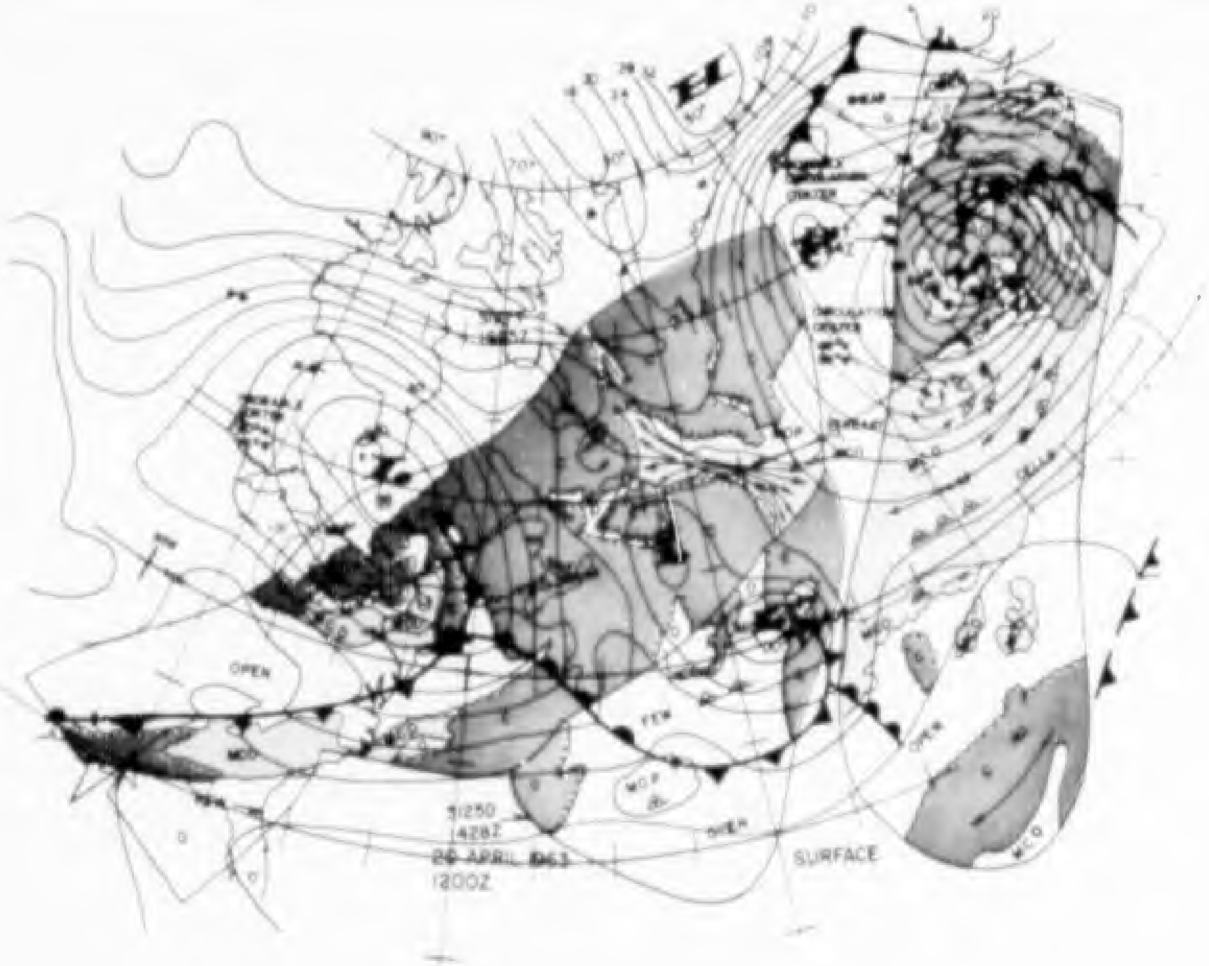


Fig. 10-19 Neph Mosaic and Surface Analysis for 0000Z, 20 April 1963; and Picture from Orbit 4363 R/O 4362 TIROS V, 1925Z, 19 April 1963



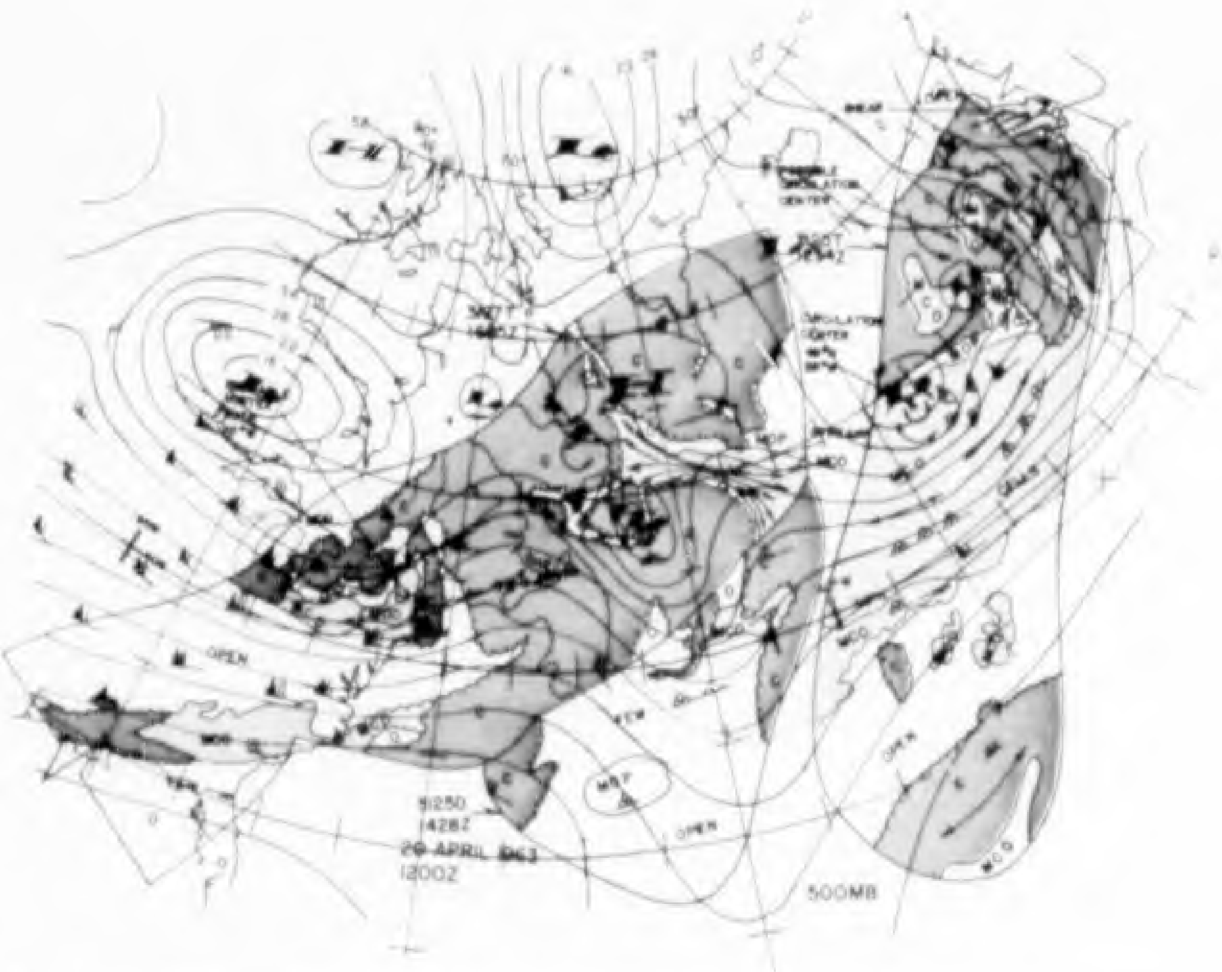
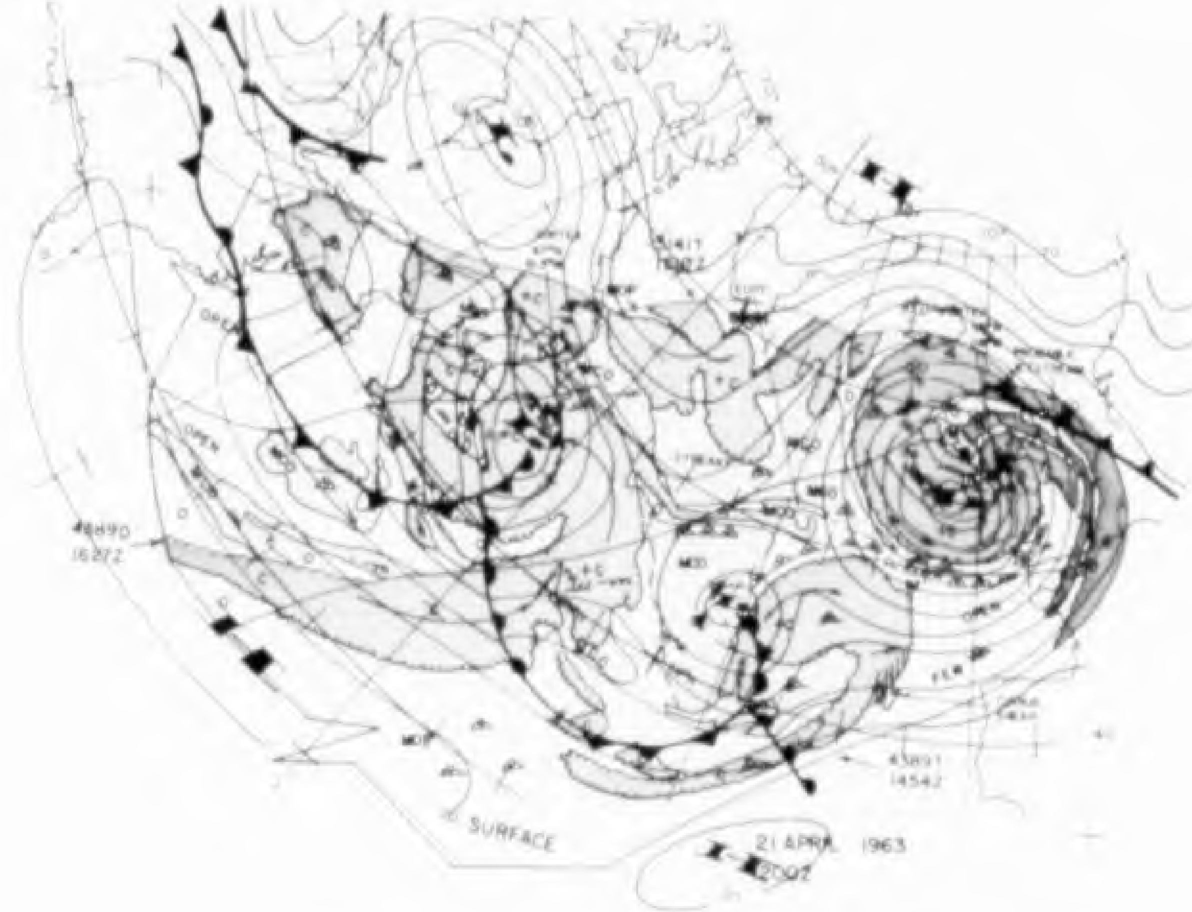


Fig. 10-20 Neph Mosaic and Conventional Analyses for 1200Z, 20 April 1963



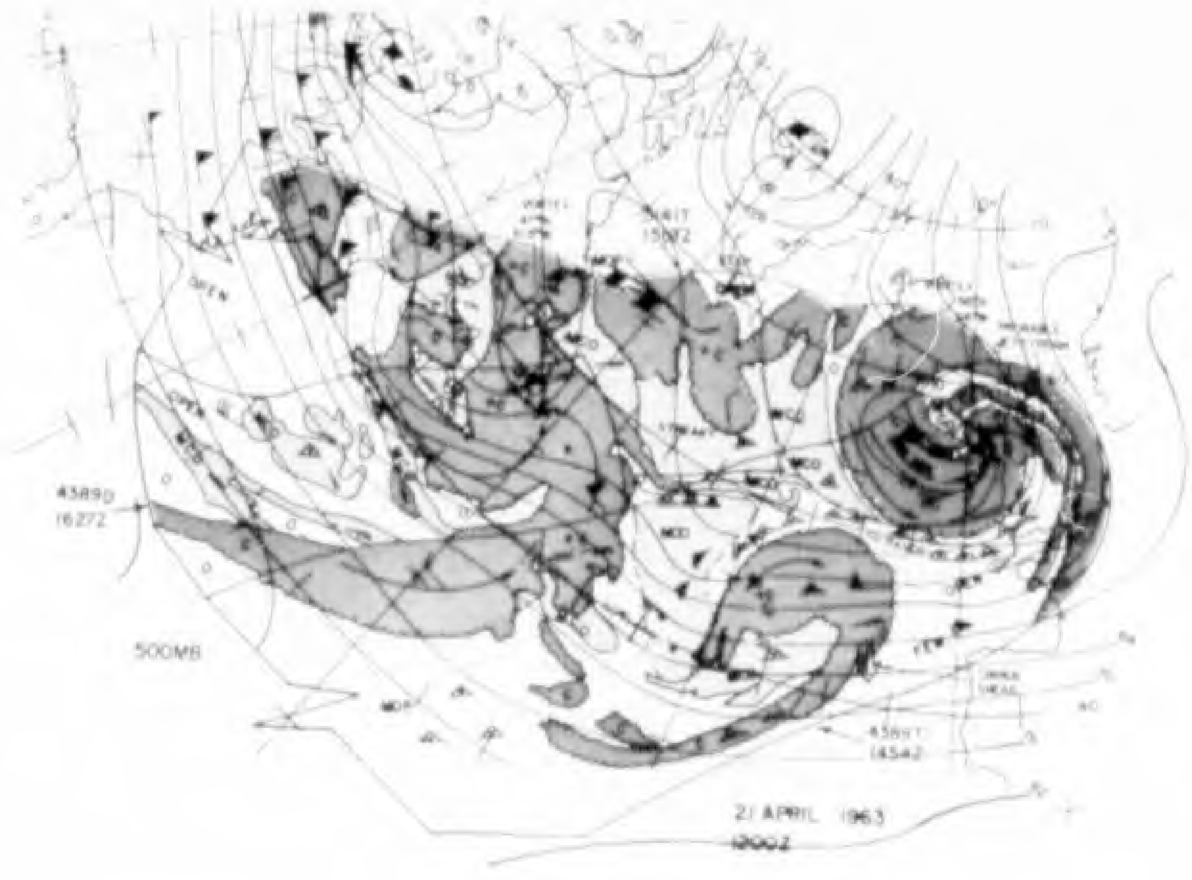
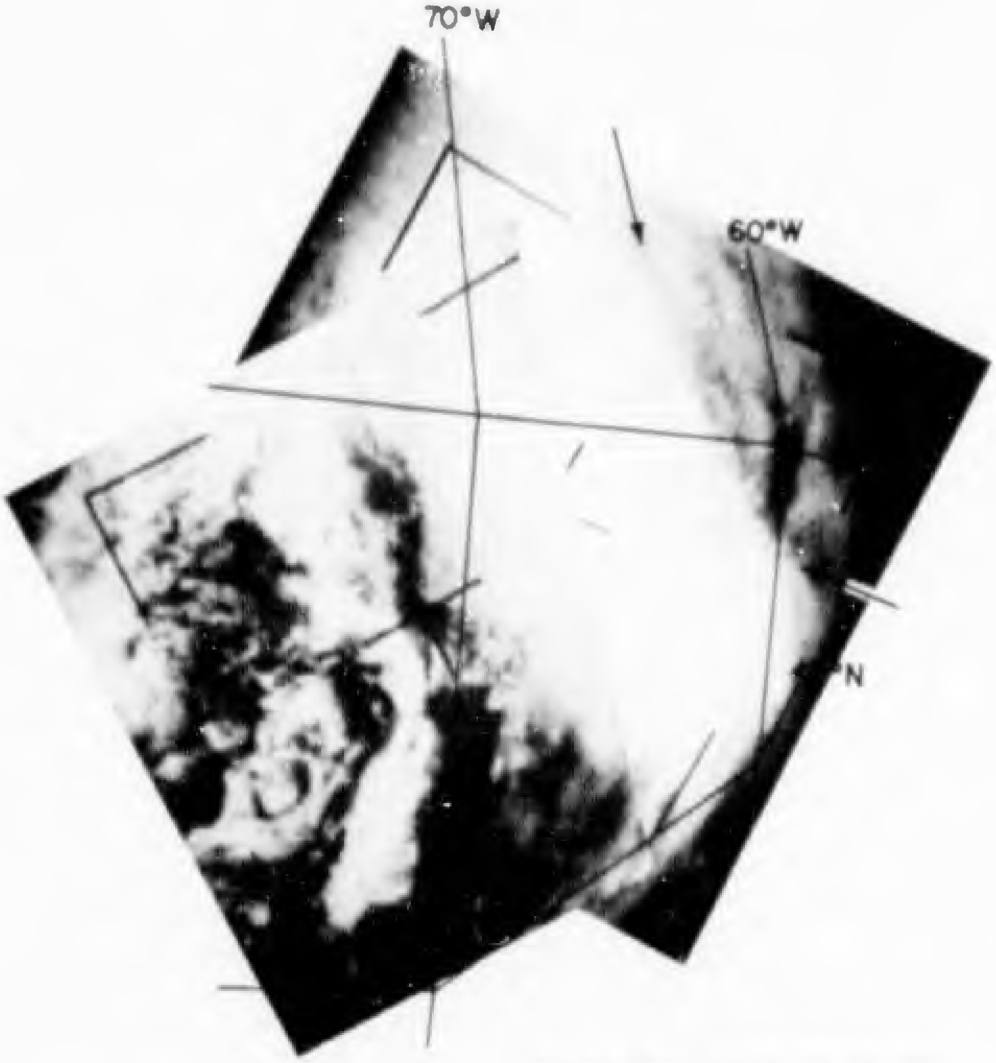


Fig. 10-21 Neph Mosaic and Conventional Analyses for 1200Z, 21 April 1963



NOTE: EASTERN BOUNDARY
OF VERY BRIGHT CLOUD
INDICATED BY ARROWS

Fig. 10-22 Mosaic from Orbit 3127 R/O 3126, 1605Z, 20 April 1963, showing the Cloud Pattern. (Note the very bright "heavy covered" area as distinguished from the "covered" areas.)

10.5.2 Applications of Synoptic Climatology

Similar reasoning applies to comparisons between analyses derived principally from satellite data, and the synoptic climatology for the area and season. This extends the probabilities of climatology to the reasonableness (for the area and season) of the deduced analysis pattern both as a whole and in its inter-relationships.

Closely related to synoptic climatological considerations and checks are the physical principles which relate the observed weather and cloud patterns to flow pattern, thermal, and frontal configurations. In most cases, this merely involves inverted use of the rules-of-thumb that have evolved over the years and which have been effective in making weather forecasts from prognostic flow patterns; when these rules are turned around, they can be used for deducing the flow from observed cloud patterns. A few of these can be stated as follows.[50]

1. In the region of the mid-latitude westerlies, the main cloud masses will lie between the mid-tropospheric trough and the downstream ridge. The relatively cloud-free area will lie between the ridge and the downstream trough. A modernized version of this rule would be that in areas of major cloud systems the mid-tropospheric vorticity advection is most likely positive (increasing upstream), since positive vorticity advection is associated with upward vertical motion. In large, relatively cloud-free areas the vorticity advection is most likely negative. In fact, it has been found[12] that virtually all cases of observed broken and overcast cloudiness occurred with strong 500-mb cyclonic vorticity advection ($> 5 \times 10^{-10}$ sec $^{-2}$), although the converse does not hold; i.e., a substantial fraction of scattered and clear cases are also characterized by strong positive vorticity advection. Higher correlations occurred with strong progressive waves aloft and with well-developed cloud systems. On the other hand weaker troughs and cut-off cold lows aloft or ill-defined cloud systems showed the poorest correlations.

As discussed in Section 6.1, these less than perfect correlations doubtlessly result in part from the use of the vorticity advection for a single level. Although there exists a rather strong relation between cloudiness and vorticity advection in the mid-troposphere the degree of association also appears to be a function of the synoptic situation, implying that other factors, such as circulation and thermal structure and their relation to vorticity advection at other levels, must be considered also. The problem of synoptic analysis and prediction is 3-dimensional in nature. Thus it is necessary to consider in so far as possible what the cloud patterns imply about the 3-dimensional structure of the atmosphere, thereby providing information for modification of not only the flow at (say) 500 mb but also at other levels.[12] This again emphasizes the need to integrate the satellite observations with other available data.

A one-to-one correlation between cloud patterns and computed vertical velocity fields (or fields of closely related parameters, such as vorticity advection) is not to be expected for several other reasons. For example, upward motion in unsaturated air will not result in clouds unless and until upward motion of the air, and the associated adiabatic cooling, is sufficient for condensation. In very dry air, there may be no condensation and cloud formation. Downward motion in cloudy air must exist for some time or have considerable magnitude before deep clouds can completely dissipate.[12] But, while it appears that no single and relatively simple quantitative field, such as vorticity advection, is directly derivable from the cloud patterns, considerable information about the three dimensional circulation and thermal structure of the atmosphere can be inferred from the satellite-viewed cloud structure.[12]

2. Where a band of frontal clouds extends well into the cold side of the surface frontal position, the flow aloft is roughly parallel to the front. Where the frontal clouds are on the warm side of the surface frontal position or are absent, the flow aloft is across the front from the cold to the warm side.

3. When there is rapid west to east motion of the main cloud system, as seen on successive satellite passes, the flow aloft is likely to be quite strong and of low amplitude. When the orientation of the cloud systems tends towards meridional, large amplitude contours are likely.

4. Where an extensive area of low clouds lies along the slopes of mountains with a sharp edge of the clouds near the peak of the ridge, the low level flow is up slope.

5. Over oceans and flat land regions, extensive areas of low clouds may be accompanied by cyclonic low-level flow. In applying this rule, however, consideration must be given to the exceptions such as those regions climatologically prone to low level stratus, as for example the ocean areas off California and West Africa, and the stratus or sea fog area in the example in Section 10.4.

10.5.3 Prognostic Charts

When an up-to-date and reasonably reliable prognostic chart can be expected to exist for a data sparse area (as, for example, over the western portions of mid-latitude oceans, where the relatively plentiful upstream continental data usually lead to a good prog), the prog chart can often assist in beginning an analysis which is to be based primarily on the satellite observations. The prog chart can indicate approximately the types of synoptic features expected to exist over the area, their location, and (unless unexpected developments are indicated by the satellite cloud pattern) the pressures and contour heights at the centers of lows and highs. The satellite data can then be used to improve and modify the analysis by showing the actual locations of the features and by identifying developments not anticipated in preparing the prog chart.

It is also suggested that NMC or other prog charts can be checked or confirmed, as time progresses, by inspection of current nephanalyses. This can be accomplished by noting the relation of the cloud patterns to conventional data over relatively dense data areas and continuing to trace the cloud patterns as they move, for example, off the eastern coast of a continent. Continued developments, changes in intensity, velocities of system translations, and movements of upper level troughs or ridges are examples of conditions that can often be monitored in this way.

10.6 GENERAL GUIDELINES FOR COORDINATION AND INTEGRATION

The operational procedures suggested earlier in this chapter have been cited for purposes of illustration. At this stage in the development of the operational use of satellite data, it is neither possible nor perhaps desirable to prescribe specific procedures for all kinds of situations. The forecaster must ultimately decide what is best in each individual case. For this purpose, the following principles are suggested as general guidelines:

1. Satellite data become most useful when fully integrated with meteorological information from all other sources. Because of this, integrating satellite cloud data with other synoptic charts is very desirable. This has the advantage of assembling as much pertinent data as possible on one chart.

2. On the other hand, in field weather stations, transpose only such data as have the prospect of being useful. Time is a precious commodity for the operational forecaster, especially during periods of critical weather. He must therefore limit his procedures to those that hold most promise of being productive.

3. The nephanalyses can provide the forecaster with data otherwise unobtainable. Compositing of the nephs and their integration with conventional synoptic analyses (or simplified version thereof) aids the operational interpretation and application of the satellite data.

4. As in all meteorological analysis, immediate past as well as currrent nephanalyses should be examined and considered. While the forecaster should not become a slave of continuity, neither should a reasonable continuity of the movement and development of systems be abandoned without reasons for so doing being noted in the data.

In some areas of the world, no conventional data exist for hundreds of miles. In these areas, it is suggested that cloud bands, comma - shaped cloud areas, cloud vortices, relatively small but bright cloudy areas, or other areas which appear to be significant can often be associated with such features as typical frontal patterns, fields of vertical motion or areas of significant vorticity advection. Often even a remote conventional observation can be tied into an analysis, once the basis for the analysis is established by the satellite data.

TROPICAL ANALYSIS

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CHAPTER 11

TROPICAL ANALYSIS, ESPECIALLY OF PERTURBATIONS AND VORTICES

The most important application of satellite cloud data has been and probably will continue to be in the analysis of cloud and circulation patterns over regions of sparse conventional data. The tropics constitute by far the largest area of insufficient and generally poorer quality meteorological data.[94] Accordingly, tropical forecasters should reap the greatest benefits from the satellite pictures. This was well exemplified by the 1961 hurricane season when TIROS gave the first indications of Hurricane Esther (Fig. 11-42) and also provided important pictures of Hurricanes Anna, Betsy, Carla (Fig. 11-32) and Debbie (Fig. 11-42).[33]

Since satellite cloud photography furnishes novel data, mid-latitude meteorologists are obtaining a new look at familiar atmospheric circulations. The tropical meteorologist is obtaining not only a new look but, in many areas, the first look at unknown or, at best, suspected circulation regimes. A truly valid synoptic climatology of the tropical regions is yet to be established. Not only must new concepts be formulated, but there remains the large task of correcting erroneous concepts which have become established as a consequence of inadequate data.[94] The meteorological satellite data offer the possibility of obtaining a reasonable description of the tropical troposphere on a global scale. It would be unfortunate if the data are forced into the framework of various current and all-inclusive (but not necessarily adequate) models which they may not fit.[96]

Satellite data permit, for the first time, useful inferences as to the synoptic distribution of significant elements in tropical areas where, previously, time sections provided the only means of deducing the horizontal distribution of meteorological parameters.[71] Even in parts of the tropics where a reasonable number of surface reports are available, the analyst must be cautious in evaluating individual observations because synoptic systems are easily masked by local effects and small inaccuracies. Significant weather-producing systems are often revealed only by a small change in wind direction and pressure, and an increase in cloudiness and precipitation, but local and diurnal effects often produce changes of equal or greater magnitude.[84] Ship reports, of course, are not affected by terrain, but small wind changes are not effectively observed from a moving ship. In the tropics the cloud reporting code is inadequate to differentiate local cumulus and showers from the clouds and showers of a disturbed situation. The normal clue to a synoptic disturbance is a larger-than-normal amount of middle cloudiness at a group of stations.[54]

Often, even when surface observations do confirm large amounts of middle clouds, it is not possible to deduce from surface observations the extent, shape, and continuity of the cloud mass. Satellite observations can ease the analysis chore and lend confidence to the final result, since they provide considerable evidence as to the existence of any significant disturbance, and some estimate of the likelihood of intensification.

In tropical analysis, perhaps even more so than in middle latitudes, it is vital to integrate both satellite and conventional data, and to make full use of immediate past and climatological data as well as current observations. Circulation features inferred from cloud pictures alone can be misleading. For example, it is often difficult to distinguish from the cloud pictures alone between low-level warm vortices (Fig. 11-1) and those restricted to upper levels (Fig. 11-2). Better interpretation results from combining satellite data with the proper tropical synoptic charts and with a knowledge of the regional climatology.[33,94]

Operational utilization of satellite data for the tropics is restricted, at present, by the lack of adequate communications. The cloud photographs, which contain the mesoscale details necessary for early detection of tropical depressions, cannot be made operationally available to most overseas tropical analysis centers. Personnel of the TIROS analysis centers may not be experienced in tropical meteorology, nor do they have access to adequate tropical analyses as an aid in interpretation. Information received from the TIROS analysis centers is, therefore, often restricted to the approximate location of significant large scale cloud features depicted in the nephanalyses. Even this information has been demonstrated to be of substantial value.[95] The fullest tropical application of satellite data will depend on the degree to which significant information is entered on the nephanalyses transmitted to field forecasters. With APT, the burden of analysis falls on the local forecaster.

It is suggested that the following techniques will aid in integrating the satellite data into an analysis and forecasting routine:[71]

1. Continuity

Since tropical perturbations are usually associated with certain conservative properties in the atmosphere, it is essential to maintain daily continuity of the satellite observations. In this way it is possible to infer changes in apparent organization and intensity.

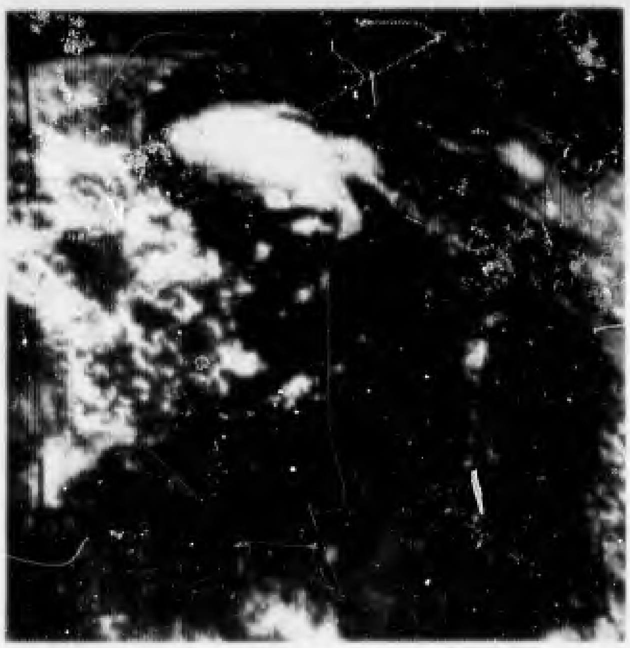

Fig. 11-1 Cloud Field Associated with Low-level Tropical Vortex

Fig. 11-2 Cloud Field Associated with Upper-level Tropical Vortex

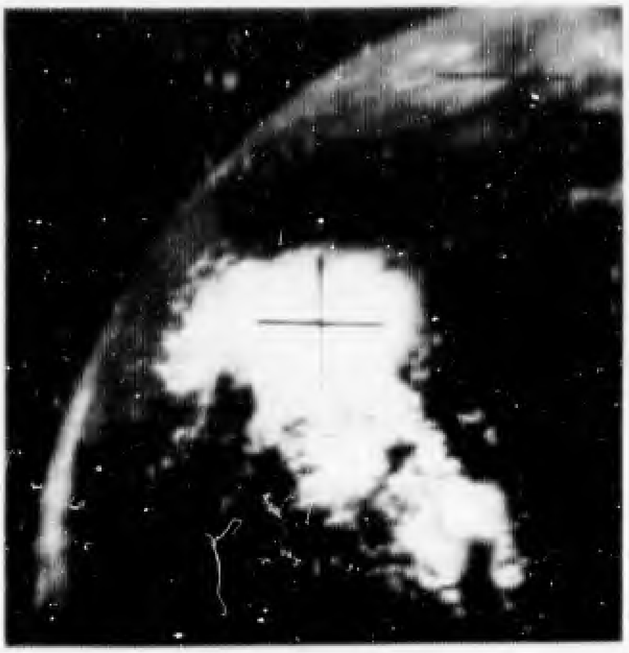

Fig. 11-3 Major, Amphorous, Tropical Cloud Mass

Fig. 11-4 Cloud Band Associated with Mid-latitude Cold Front Moving into Tropics

2. Time Cross-Sections

Time cross-sections are still among the most useful of all tropical techniques. The integration of the satellite nephanalyses with these cross-sections will provide a combined vertical and horizontal picture of the tropical atmosphere heretofore unobtainable (see Section 11.12.4).

3. Streamline Analyses

Streamline analyses have been used for many years in tropical analysis. The selection of analysis levels has largely been governed by operational aircraft planning needs, and mid-latitude concepts. Recent studies[71,73,74,97] have indicated a distinct relationship between the development of major tropical perturbations and mid-troposphere streamline patterns; 14,000 ft is suggested as a particularly useful analysis level because it appears to be most closely related to the observed perturbations.

In the upper troposphere, the usefulness of satellite information showing cirriform outflow streamers (see Sections 11.5.1, 11.5.3 and 11.6.3) can be increased by streamline analysis at a level which is near the mean tropical cirrus formation height; 37,000 ft has been used with good results.[71]

Tropical meteorological phenomena, in a general sense, are not regional. When treating any specific phenomenon, however, it is vitally necessary to take account of the appropriate regions of occurrence. For example, cloudiness relating to the equatorial trough zone of the North Atlantic is displaced north of the geographical equator throughout the year due to the location of the West African land mass whereas, in much of the Pacific, the average annual distribution of the trough zone cloudiness is fairly symmetrical with respect to the equator. The manner of apparent initiation of tropical storms also varies regionally; e.g., in the western Pacific many tropical storms originate in the equatorial trough zone, while, in the Atlantic, only a few appear to develop in this way.[72]

Tropical research with meteorological satellite data has necessarily concentrated on relatively limited geographical regions. This chapter is necessarily based on such limited research. While it is anticipated that many of the findings are applicable to other tropical regions, this cannot be assured without further research.

Appendix D provides more specific discussion of the two most investigated regions: the eastern North Pacific, and West Africa and the eastern North Atlantic.

11.1 SIGNIFICANT TROPICAL FEATURES AS SEEN BY SATELLITES

There are three major types of tropical cloud patterns which are frequently obvious in the satellite pictures and which can, in many cases, be used as starting points for the overall analysis.

11.1.1 Amorphous Cloud Masses

Major, amorphous, cloud masses (Fig. 11-3) are without any distinct recognizable pattern. Some authors have referred to them as cloud "blobs".[95] Such cloud masses may be found isolated, or associated with cloud bands. These cloud masses, especially when associated with a monsoonal trough* or climatological zone of convergence, or with a major cloud band, should be examined for signs of system intensification, using both available conventional data and day-to-day continuity. It is difficult to identify, with any degree of confidence, which of these cloud masses are associated with developing storm systems,[95] or upper level disturbances,[94] except by watching their day-to-day development and/or comparing them with indications provided from conventional data and analyses.

11.1.2 Cloud Bands

Major cloud bands are usually associated with some pattern of wind convergence and/or horizontal shear. They may result from a mid-latitude cold front which has moved into the tropics (Fig. 11-4), with the clouds and some degree of convective weather and showers persisting after all air mass contrasts have long been lost. Cloud bands are often found in monsoonal troughs, or near them,along associated convergence lines (Fig. 11-8a). They may also be indicative of other areas of shear or convergence associated with synoptic scale flow patterns (Fig. 11-5) or with major troughs apparently fundamental to the organization of the tropical portion of the general circulation. In some cases, the related flow or streamline patterns are apparent only in the upper troposphere, although the associated weather may be felt at the surface.[19]

* A trough featured by seasonal changes in the direction of the prevailing winds.

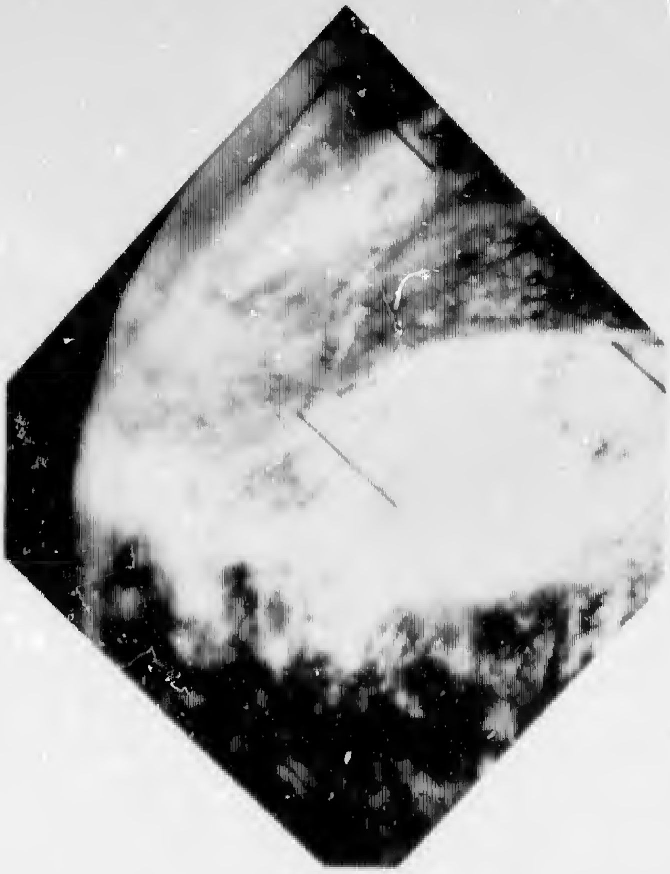

Fig. 11-5 Cloud Band Associated with Area of Convergence in Tropical Synoptic Scale Flow Pattern

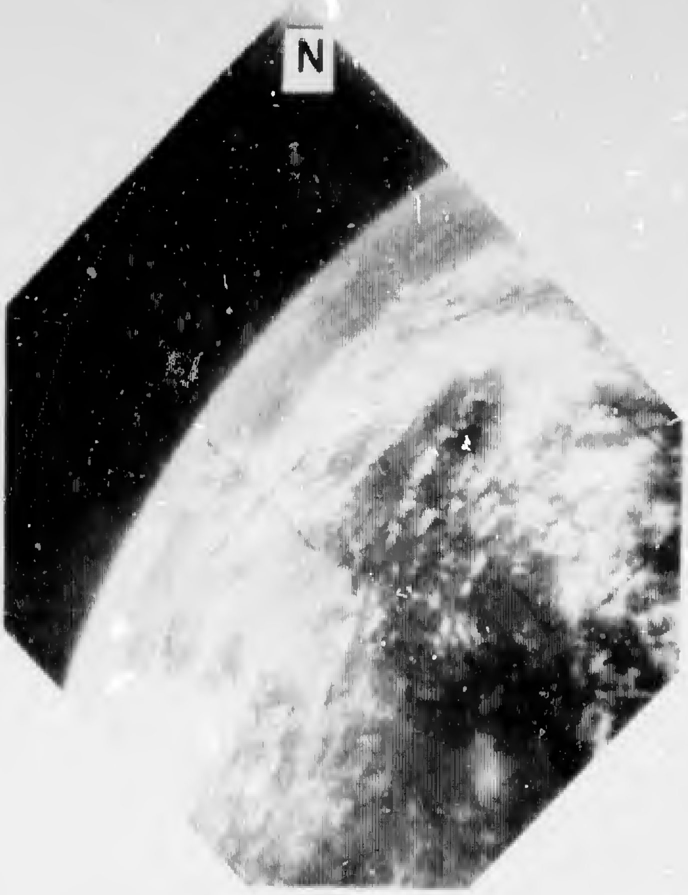

Fig. 11-6 Formation of an Easterly Perturbation, "Bending" Pattern

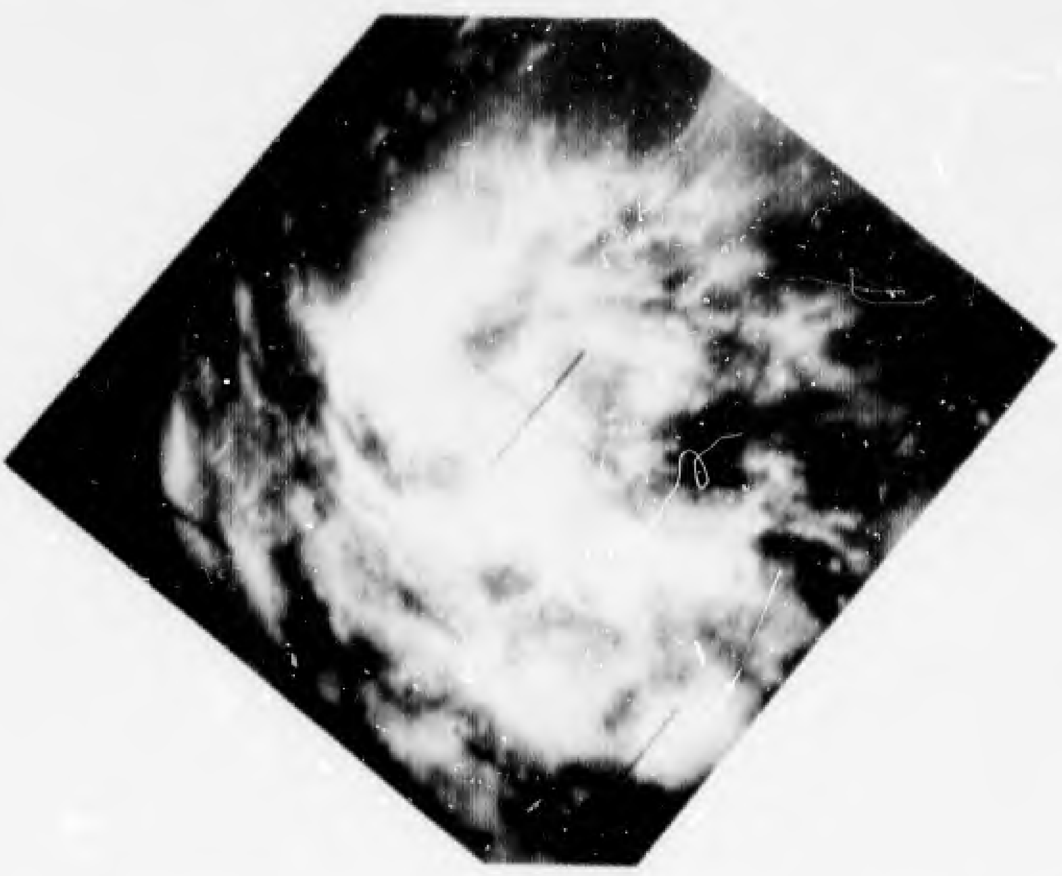

Fig. 11-7 Formation of an Easterly Perturbation, "Folding" Pattern

Any distorted area of significant size found along a band, such as a bend, fold, bulge, etc., is possibly indicative of a developing disturbance (Fig. 11-6). While other cloud patterns are often in existence during the early stage of tropical vortex development, there are indications that the initial impulses appear in the major cloud bands,[8] especially those in or directly associated with monsoonal troughs and convergence zones.[94]

While there have been a number of instances where significant bands of clouds have existed without corresponding systems being apparent in conventional analyses, the forecaster is cautioned against minimizing their importance. The existence of these bands implies either the current or recent existence of organized upward motion. This upward motion is usually of some practical importance, regardless of the cause to which it can be directly ascribed.[50]

11.1.3 Vortex Patterns

Vortex cloud patterns in the tropics may be associated with disturbances with a wide range of intensity, ranging from mere tropical disturbances (Fig. 11-16) to severe hurricanes or typhoons* (Fig. 11-19). Developing tropical cyclones will exhibit vortex cloud patterns (Fig. 11-16) when maximum wind speeds are still below tropical storm intensity.[97] Indicators of storm intensity will be discussed in subsequent portions of this section.

11.1.3.1 A Vortex Development Sequence

In part for convenience of organization of the discussion, later portions of this chapter will emphasize tropical vortex patterns following a development sequence somewhat analogous to that for extratropical vortices, since this appears to be a particularly frequent case. A disturbance in a major convergent band (Figs. 11-6, -7) or in some cases a heavy isolated cumuliform cloud mass (or cloud "blob", Fig. 11-3), indicates the Tropical Disturbance stage. Tropical depressions and

* In the remainder of this chapter, the term hurricane will frequently be used to denote a severe tropical cyclone without regard to the normal geographical implications of the terms "hurricane" and "typhoon".

weak tropical storms can be identified by distinct, concentric cumuliform banding (Fig. 11-16) without the pronounced and more symmetrical cirriform canopy so noticeable in intense tropical storms (Figs. 11-17, -18) and hurricanes (Fig. 11-19). Hurricane force winds are associated with those well organized cases where the cirriform clouds nearly obscure the cumuliform banding (Fig. 11-19). When decay is over water, the storm degrades through a reverse sequence similar to the later development stages (Fig. 11-36). Over land (Figs. 11-38, -39), decay is much more rapid and marked changes occur.[8]

11.2 TROPICAL CLOUD BANDS

11.2.1 Convergence or Shear Lines

At least one type of tropical cloud band is associated with cold air penetrations into the tropics and the remains of cold fronts (Figs. 11-4, 5-21). Extensive cloud bands in lower latitudes indicate that the effects of such penetrations of cold air from the north are long lasting, with the cloud band remaining as a significant feature long after means to detect fronts on a conventional basis have been lost.[102] Having traveled many days over a warm ocean surface, such convergence or shear lines no longer represent air mass boundaries. Nevertheless, a band of cloudiness and frequently an accompanying line of shear may retain their identities for several days.

Such systems are significant, since it is clear that they are self-perpetuating. Furthermore, since they often become quasi-stationary, these systems may remain undetected for long periods because they do not sweep across reporting stations as do waves and vortices.[54] For this reason, the satellite can be invaluable for observing such systems, and for following their subsequent motion and modifications.

In at least one case, such a cloud band has been shown to follow the motion of the convergent streamline asymptote between subtropical anticyclones, marking the convergence between flow in the equatorward limb of the anticyclones and the trade wind easterlies.[54] Even a dense (by tropical standards) network of surface observations may provide only a rough indication of lines of convergence in the low troposphere. Based on surface cloud data, the presence of disturbed weather near such a major convergence line (Fig. 11-5) may be suggested, but from surface reports alone it is often not possible to determine the extent, continuity, or intensity of such a line. But the available standard data, complemented by cloud observations from satellites, can lead to a far improved analysis of the actual situation.

11.2.2 Monsoonal Trough Convergence Lines

Convergence lines and associated zones of heavy cloudiness are also found related to monsoonal troughs over the tropical oceanic areas. At least in the eastern North Pacific in the summer season, the principal convergence zone and related cloud band has been found located not along the trough itself, but some 2 to 3 degrees south of the trough line where convergence takes place between the westerlies on the south side of the trough and the flow from the southern hemisphere which turns anticyclonically from southeast through south to southwest (Fig. 11-8). The cloud patterns suggest the northern edge of this convergence is usually rather sharp as opposed to the feathered or ragged appearance of the southern portion. There may be a secondary line of convergence and associated cloudiness, located to the north of the trough line and also displaced from the wind-shift line. This zone is frequently absent and when present is much less intense than the southern convergence zone.[96] Similar patterns appear to exist in other climatologically similar areas, such as the tropical eastern North Atlantic.

Proper interpretation of major cloud bands associated with solely upper level troughs (Figs. 11-9a, c), without reflected patterns of lower level winds and pressures (Fig. 11-9b), requires proper coordination of the satellite data with a knowledge of regional climatology and all available synoptic data. Otherwise, the unsuspecting analyst may attempt to account for widespread cloud bands and associated precipitation by placing an erroneous and forced "easterly wave" on the low-level charts.[94]

The first evidence of potential tropical storm activity may be the existence of an intense cloud band. While other cloud patterns are often in evidence during the early stages of tropical storm development, the semicontiguous zonal cloud bands which are frequently observed in the tropical regions of the Atlantic and Pacific are believed to be the location where initial perturbations occur which lead to the development of many tropical cyclones.[8, 26] Figure 11-10 shows an example of such a well-defined band near the West African coast. Recent evidence suggests that even the disturbances relating to or mistakenly analyzed as waves in the easterlies have their origin in these zonal cloud bands, rather than within the deep easterlies.[71]

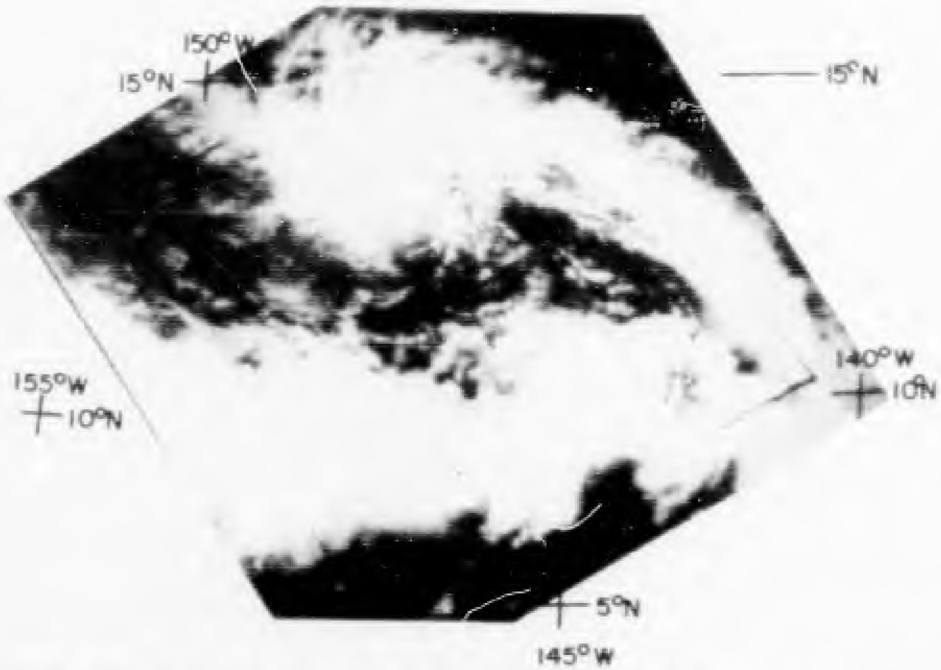

Fig. 11-8a Convergence Lines Associated with Monsoonal Trough in Eastern North Pacific

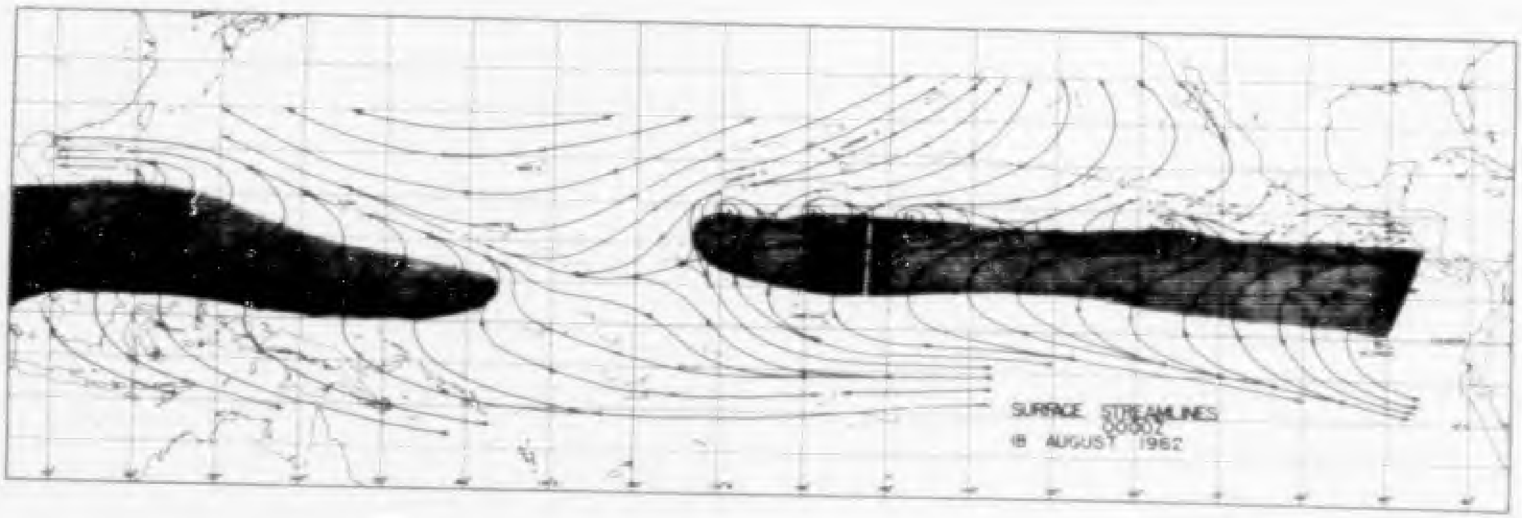

Fig. 11-8b Surface Streamline Analysis of Tropical Pacific for 0000Z, 18 August 1961. Winds of Westerly Component Indicated by Shading (From Reference 90)

11.3 PERTURBED TROPICAL CLOUD BANDS

The first strong indicator of one form of tropical storm formation is most probably some clearly apparent distortion of a major cloud band,* although many such distorted cloud bands may never develop into significant disturbances.

This distortion may take the form of:

1. Bending (Fig. 11-6), with the pattern representing the classical concept of a distortion of the convergent-formed cloud bands by a "surge-in-the-trades." A low center may form along the band, with stations to the north experiencing passage of a wave in the easterlies.[71]

2. Folding (Fig. 11-7), with the cloud pattern appearing to achieve a vortex-like pattern by a folding up, accordian fashion, of a zonal cloud band.[71]

3. Budding or bulging of the cloud band (Fig. 11-11).

If development continues, the first signs of a definite cyclonic rotation become apparent as a result of further distortion of the major cloud band. At this stage, surface conditions in the vicinity of the disturbance should show increased rainfall, but little or no change in winds or pressure. Several examples of this stage have been observed in each of the major tropical cyclogenetic areas.[8]

Because of the close association between major tropical cloud bands and monsoonal troughs, the view has also been taken that initial low-level perturbations, from which most of the eastern North Pacific tropical storms form, are vortices embedded in the monsoonal trough. Such troughs are the principal "centers of action" for formation of tropical storms in the western North Pacific, North Indian Ocean, South Indian Ocean, South Pacific Ocean, and western Caribbean. A logical, consistent picture of global tropical storm formation would require that the majority of initial perturbations, from which Atlantic and Caribbean hurricanes form, be vortices which propagate westward from the monsoonal trough of West Africa. It is of more than passing interest to note that the unstable easterly wave model proposed by Riehl,[90] and based on Caribbean data, contains a vortex between 10,000 and 15,000 ft., which is the level at which vortices over and to the west of Africa are most intense.[53,73,97]

There are other patterns which have appeared at about this stage of development and which might well be included in this category, but it appears that most of these are associated with downward development of a cyclonic center aloft[8] (see Section 11.12.3).

* The other is the isolated, heavy cumuliform cloud mass (or cloud "blob"), with an absolute minimum of organized cirriform cloudiness (Fig. 11-12).

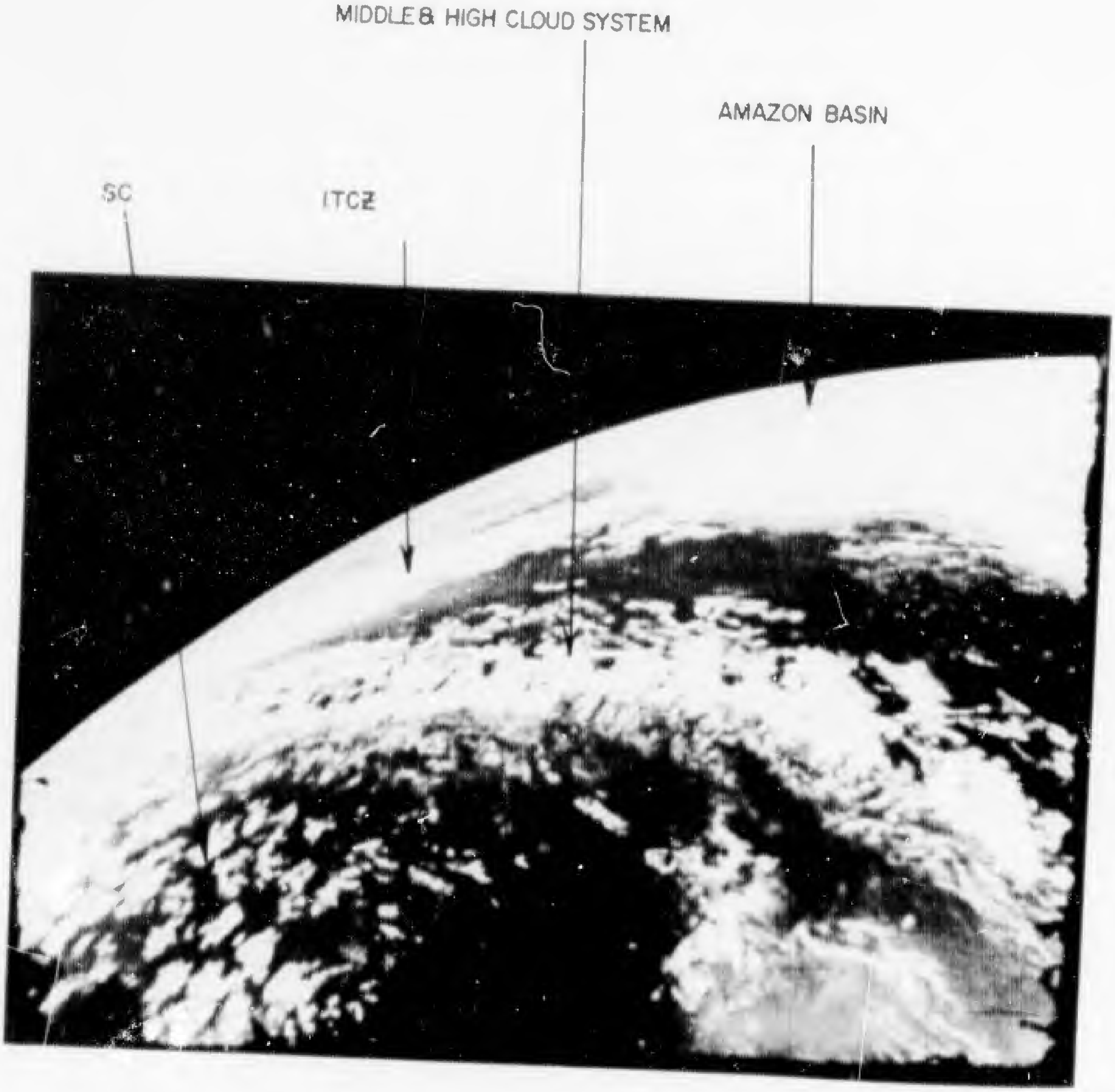

Fig. 11-9a High Altitude Tropical Cloud Band as Photographed from an Altitude of 690 mi. on 24 August 1959 (From Reference 19)

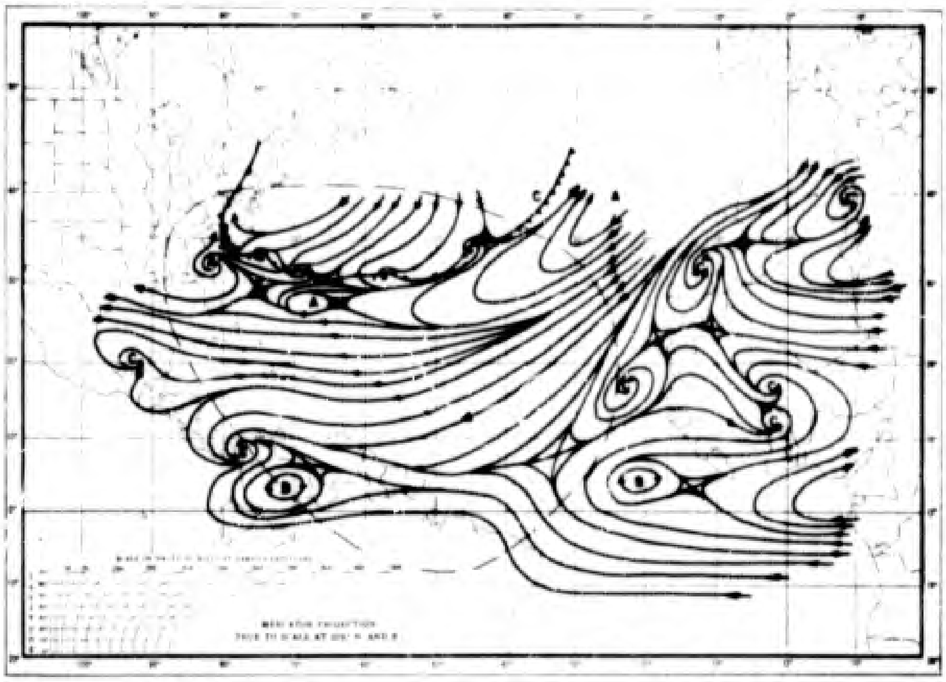

Fig. 11-9b Surface Streamline Chart, 1200Z, 24 August 1959. (From Reference 19)

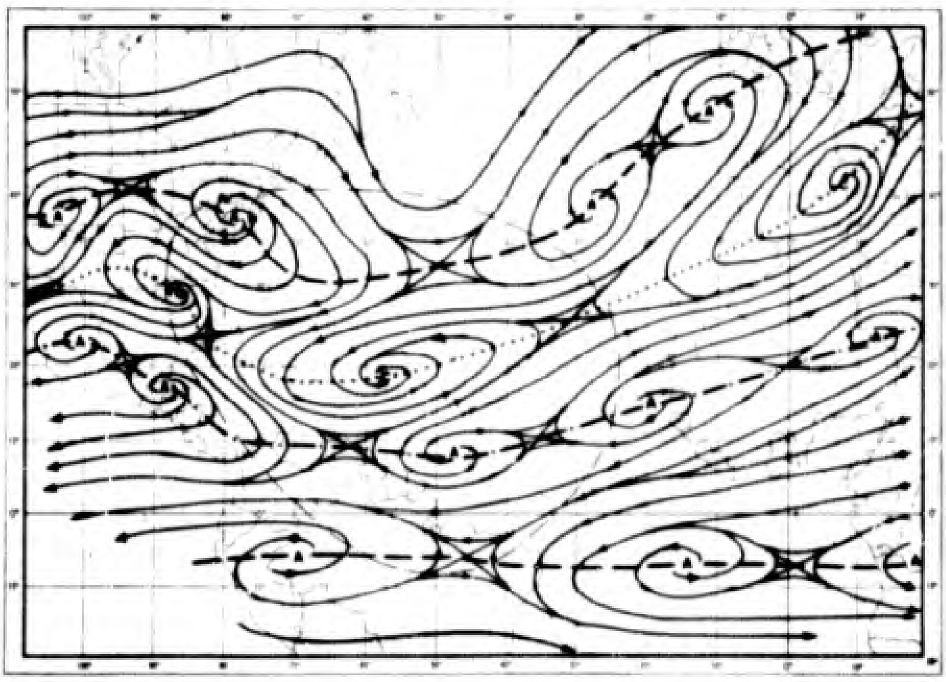

Fig. 11-9c 250-mb (35,000-ft) Streamline Chart, 1200Z, 24 August 1959. Tropical Trough, Dotted; Tropical Ridge, Dot-dashed; and Subtropical Ridge, Dashed (From Reference 19)

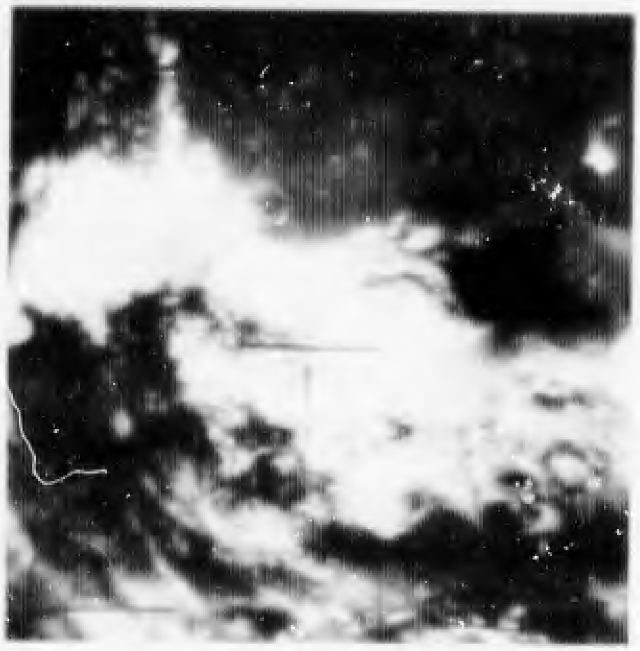

Fig. 11-10 Well-defined Cloud Band Near West African Coast

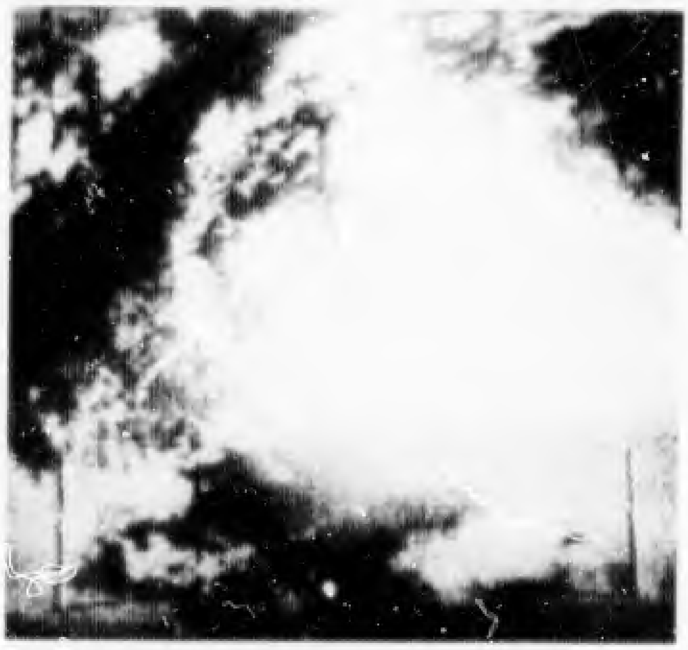

Fig. 11-11 Formation of an Easterly Perturbation, "Budding" Pattern

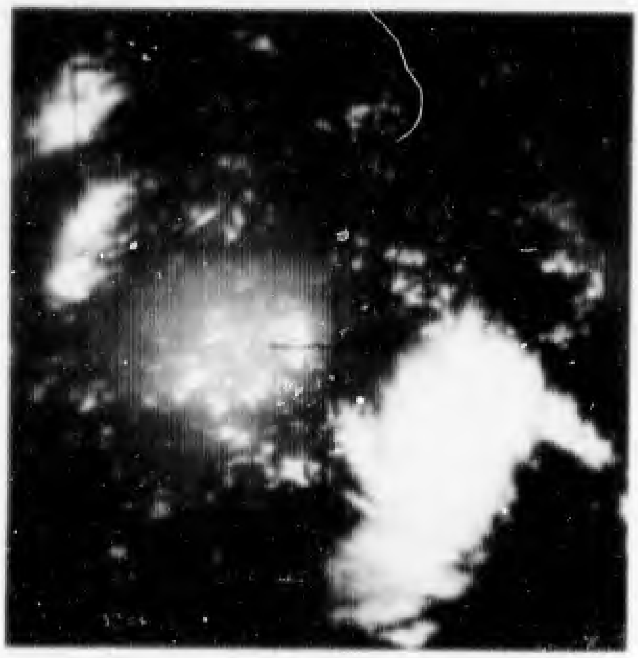

Fig. 11-12 Isolated, Heavy Cumuliform Cloud Mass as First Strong Indicator of Tropical Storm Formation

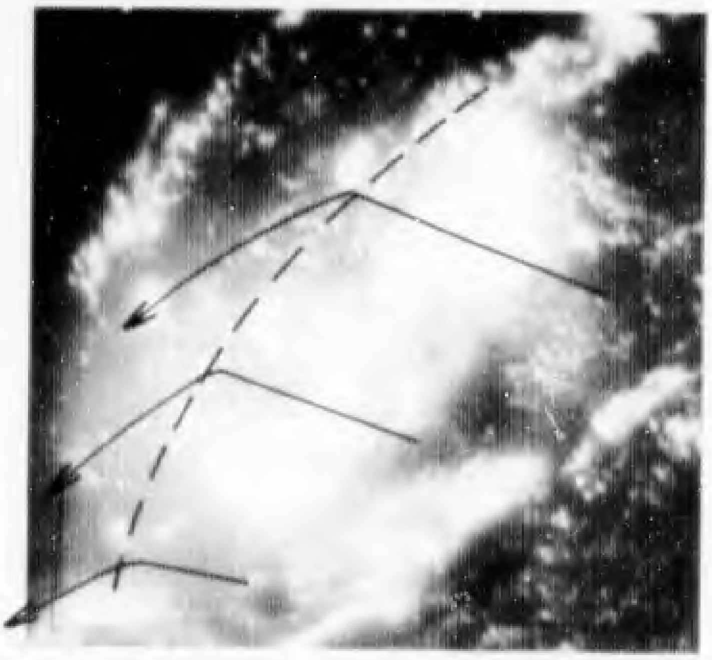

Fig. 11-13 TIROS V Photograph of Easterly Wave

11.4 TROPICAL DISTURBANCES AND WEAKER TROPICAL STORMS

At this point in the discussion of tropical storm development as observed from satellites, it seems desirable to point out that while the concept of the Easterly Wave as originally proposed by Riehl[90] is still useful for forecasting in the tropics, investigations based on satellite data indicate that it does not adequately describe the highly varied distributions of cloud, precipitation, winds, etc., which are associated with perturbations in the tropical easterlies.

11.4.1 Easterly Perturbations

It would appear that much of the confusion and controversy concerning the Easterly Wave concept has resulted from the lack of other synoptic models matching these variations in the distribution of meteorological parameters associated with perturbations in the easterlies, and the consequent tendency to attempt to force an easterly wave configuration into the analysis whenever any perturbation less intense than a tropical cyclone (or weather that cannot be associated with an existing low level system) is detected in the tropical easterlies. This subversion of Riehl's model has consequently detracted from its validity in those cases where it does apply. It has also led to a confusion in terminology whereby any, seemingly minor (from conventional data) disturbance in the easterlies has come to be referred to as an easterly wave. The more general class of disturbances in the easterlies might better be termed easterly perturbations; while these include easterly waves, the term should usually be applied with particular reference to those disturbances not fitting true easterly waves. It would now appear that, because of limitations in the data available to him, Riehl[90] included examples in his original paper on easterly waves which would now seem from analysis of satellite observations more properly to fall into other parts of the more general easterly perturbation category.[71]

Satellite studies have confirmed that Easterly Waves do exist (Fig. 11-13), with the classic distribution of a more or less continuous cloud band or mass just to the east of the wave crest. Such waves do, however, appear to be of a smaller scale than indicated in previous studies and to have a small frequency of occurrence.[71]

The cloud distribution related to an easterly perturbation which appears most frequently has a vortical appearance (Fig. 11-14) and appears to be associated with a closed cyclonic circulation in the mid-troposphere near 14,000 ft. The existence of these mid-tropospheric closed circulations was noted by Riehl,[90] but time cross-

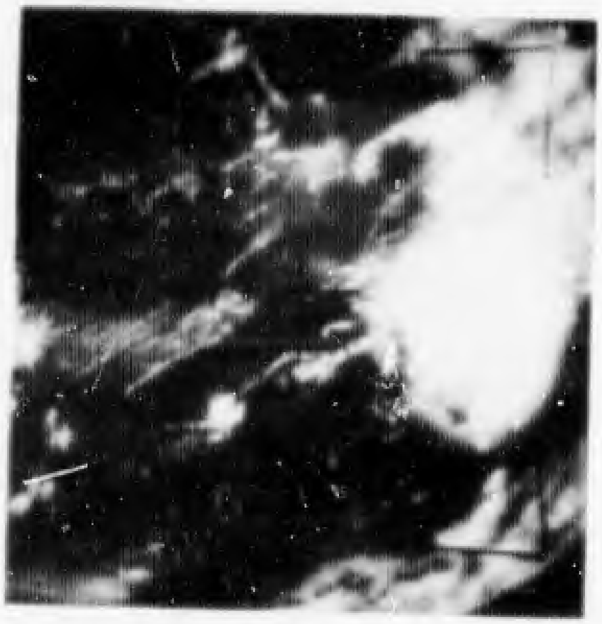

Fig. 11-14 TIROS V Photograph of Moderately Intense Perturbation

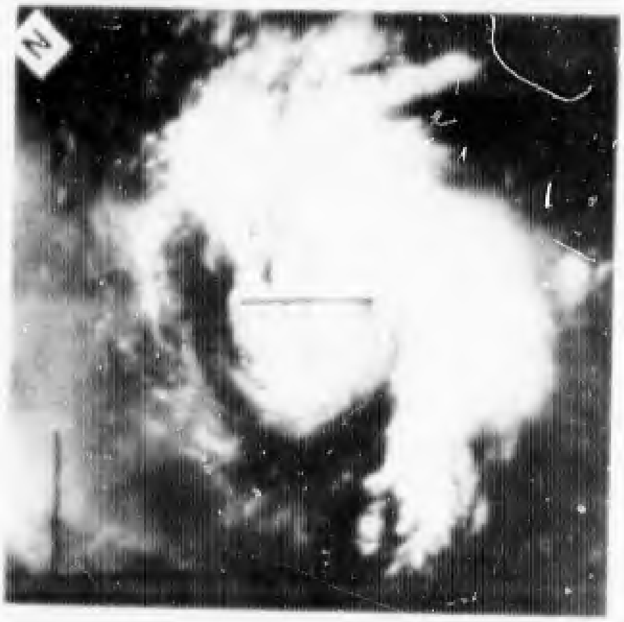

Fig. 11-15 TIROS V Photograph Intense Perturbation (Tropical Disturbance)

Fig. 11-16 Weak Tropical Storm

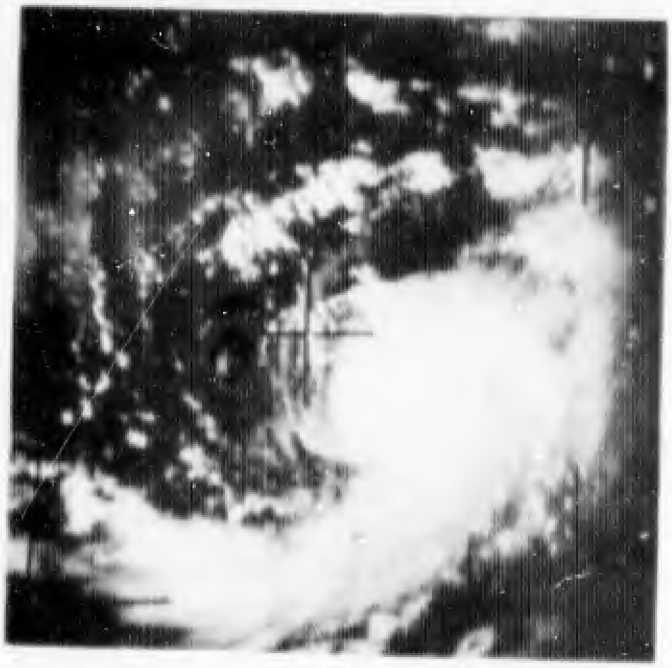

Fig. 11-17 Intense Tropical Storm

sections did not allow him to infer the related cloud distribution. These can now be determined from two-dimensional horizontal cloud information provided by the satellite.

When the mid-tropospheric circulation is intense, these disturbances are analogous to the classic unstable easterly wave. Surface flow pattern development appears to follow development of a satellite-observed vortical cloud pattern, implying downward penetration from the mid-troposphere.

Most easterly waves and perturbations examined over the Atlantic appear to have their origins in cloud bands which appear like those in an intertropical convergence zone and which are located near West Africa (Fig. 11-10), in the central Atlantic, or occasionally near the South American coast[71] (Fig. 11-9a).

Moderately intense easterly perturbations (Fig. 11-14) appear to be related to mid-tropospheric closed cyclonic circulations which extend through a very shallow layer (approximately 10,000 ft) while intense ones are associated with a deep (approximately 20,000 ft) layer within which a closed cyclonic circulation is dominant. In the case of one intense easterly perturbation (Fig. 11-15), cyclonic relative vorticity extended through a layer from about 4,000 ft to 20,000 ft and was topped by anticyclonic relative vorticity above 30,000 ft. This basic structure is probably applicable to all easterly perturbations which have a vortical cloud distribution.[71, 74]

11.4.2 Low Level Disturbances

When, at this stage, development occurs at (or also at) a low level rather than merely in the mid-troposphere, a tropical storm definitely appears to be in progress on the surface. However, winds of hurricane force are not yet present. Major cloud banding is still closely associated with the vortex pattern, but the spiral banded pattern of the vortex (Fig. 11-16) has become a clearly visible key feature in the photograph.[8] A cloud vortex may become distinctly visible with surface winds as low as about 25 knots, and may thereafter persist until the winds drop to about 15 knots.[97]

Whether development takes place at the surface or only aloft, at this stage the vortex is often clearly defined and may be mistaken for a mature tropical cyclone. Significant differences exist, however, which can provide the proper interpretation. Tropical disturbances and weak tropical storms have a pronounced lack of a fully symmetrical cirriform canopy; at this stage an unobscured banded structure visible from the satellite will exist over the entire area of the storm (Fig. 11-16). There is, however, considerable variation in the amount of apparent cirriform cloudiness which is visible in this stage. Nevertheless, while there may be definite cirriform cloudiness, the lower spiral banding is always clearly visible.[8]

11.4.3 Intensification Indicators

At the stage of intensity approximating transition from tropical disturbance to weak tropical storm, the satellite pictures usually provide an indicator as to whether or not further intensification is likely.[75] If the apparent center of circulation* shifts from the east side of the central cloud mass to the west side, and the boundary between the bright central cloud mass and the normally clear area roughly to the west (or toward the direction of storm motion) becomes marked by a smooth bright cloud edge (Fig. 11-17), intensification will often occur. Concurrently, the area of more conspicuous minor cumuliform bands will tend to shift from east (or behind) to west (or ahead) of the storm. If, however, the circulation center remains on the east or southeast side, the other changes will seldom occur, nor is the system likely to intensify during the following 24 hour period.

Since these changes occur at the time when the transition from a cold core to a warm core system has often been observed in an intensifying storm, one can speculate that this may be a visible indicator of this transition. It may, furthermore, signal the time at which a circulation, formerly most pronounced at levels near 14,000 feet, reaches and is significantly affected by surface influences.

Many perturbations reaching the tropical disturbance stage will exist for many days without significant change in intensity. In such cases, the shift of the circulation center and the other related changes in the cloud features are unlikely. The eventual fate of such non-intensifying systems can be either an ultimate intensification (usually signaled by the cloud features as described above), or dissipation without ever exceeding the intensity of a tropical disturbance.

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* As determined by extrapolating the inward spiraling of the minor cumuliform bands - see Section 11.11.

11.5 INTENSE TROPICAL STORMS (Just Short of Hurricane Strength)

At this stage of development, some cirriform cloudiness will almost certainly be visible (Fig. 11-17). Cirriform organization into a canopy may be evident although the banded structure of the storm should still be apparent in certain quadrants of the system.[8]

In this and the following (and most intense) stages of storm development, the extent and organization of the cirriform cloudiness, and of features expected to produce it, appear to be well related to storm intensity and its changes. Penetrative convective cumulus towers have been found to be associated with developing vortices (Fig. 11-20). The size of the cirriform canopy provides a representation of the strength of storm outflow, with cirriform streamers (Fig. 11-21) providing evidence of the initiation of deepening. These points emphasize the need for clear differentiation between cumuliform bands and cirriform streamers in the interpretation of the cloud pictures and on the nephanalyses.

11.5.1 Cirriform Canopy Organization

The tropical cyclone is basically an organized convective system in which the convective activity is restricted to the central core area and to portions of the spiral bands. These relatively isolated convective regions restrict vertical ascent and condensation to limited areas of the storm.* Since the amount of convective area is roughly proportional to the intensity of storm development, and, furthermore, such convective regions are the main producers of cirrus streamers in the storm area, cirrus cloudiness appears to increase in amount and organization during the development period. Such changes in cirriform cloudiness are noticeable in satellite photographs and are keys to intensity determinations. Figures 11-18 and 11-19 illustrate typical cloud organization changes as they occurred during the development of typhoon Wanda-1962, particularly the filling in of the northern half of the storm with cirriform cloudiness and the increased circulatory appearance in the "eye" area.[8]

* For example, on the day of maturity, Daisy-1958 was estimated to have only four percent of the total storm area dominated by intense convective activity; and this was the maximum percentage reached.

Time continuity is important for determination of the stage of development and for inferring intensity variations. The previous days' data should be available so any changes in organization can be noted.

11.5.2 Existence of Penetrative Convective Towers

Penetrative convective towers as observed* in tropical cyclones appear to play an important role in the development sequence. In some cases, small circular, relatively bright areas can be seen in the satellite pictures, usually near the center of apparent circulation. They are most easily seen during early stages of storm development, prior to the formation of masking cirrus and so the attainment by the storm of full maturity. Figure 11-20 shows an example of these "towers" as observed on October 4, 1962, in hurricane Daisy. Hurricane force winds were first observed by reconnaissance aircraft at about the time of this photograph. The appearance of these cells (or groups of cells) suggests that they may have only recently become visible as a result of the spreading of the cumulonimbus anvil at the tropopause.

In the sequences investigated to date, these penetrative towers were always observed in association with a developing vortex. This is suggestive of a direct relationship between the future intensity of tropical storms and the existence of these cells, but a larger sample of both deepening and non-deepening storms would be desirable before definitive statements are justified.[8]

11.5.3 Cirriform Streamers

The cirrus streamers which emanate from major convective areas of a storm are clouds now moving in the wind flow at their level. Such clouds can be present many miles from their origin; the edge of such an ice cloud may lie several hundreds of miles beyond the region in which the air associated with the cloud begins its slow descent. Down wind diffusion and evaporation will tend to produce a satellite-observable gradient of cloud brightness indicative of the wind direction at the cloud level, i. e., the wind will blow toward the less dense ends of the streamer.[8,71]

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* Probably as groups of towers.

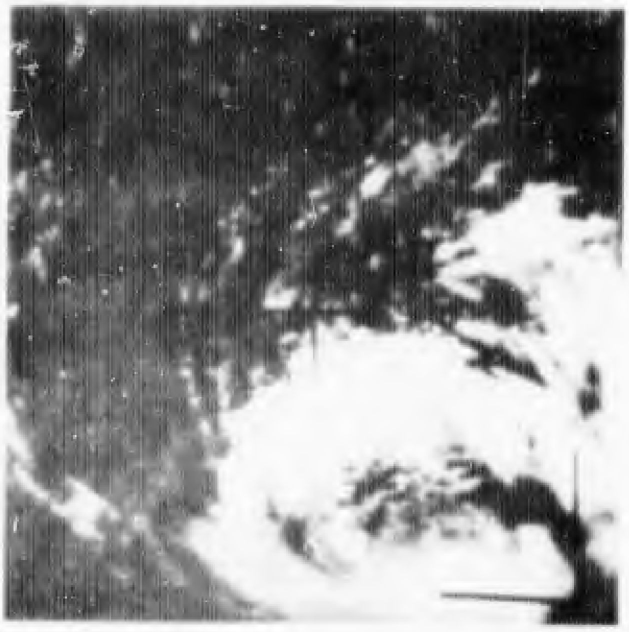


Fig. 11-18 Tropical Storm Wanda, August 29, 1962

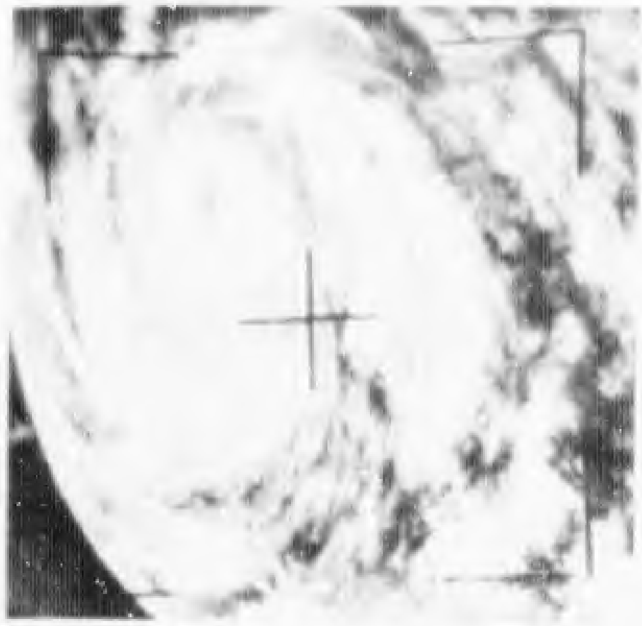


Fig. 11-19 Typhoon Wanda, August 30, 1962

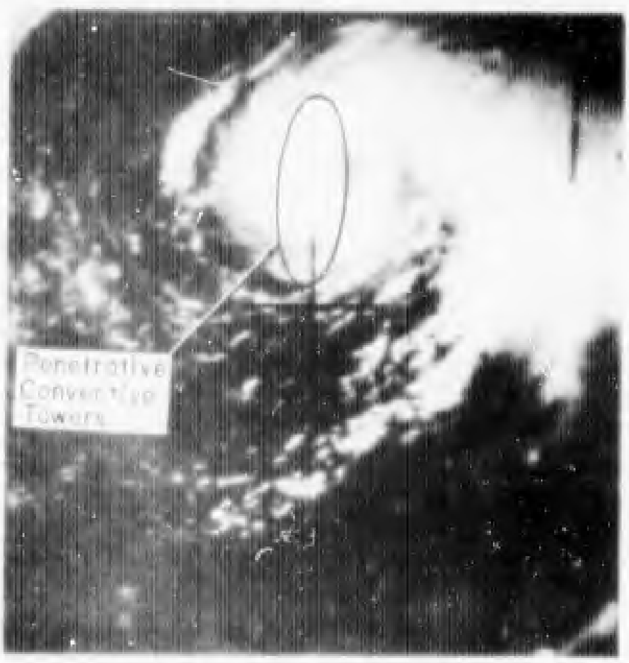


Fig. 11-20 Penetrative Convective Tower

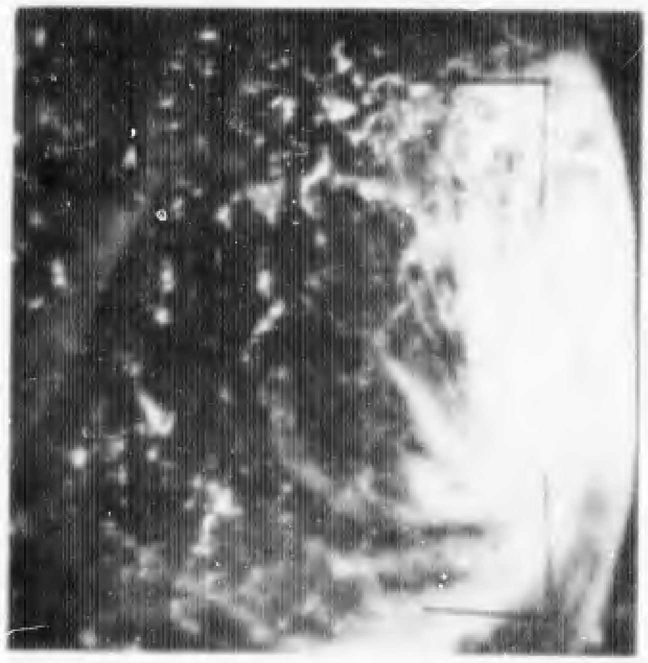


Fig. 11-21 Intense Tropical Storm Karen During Period of Deepening, November 9, 1962

When the upper outflow in a rapidly deepening, non-steady-state storm is quite intense, the satellite photographs often show cirriform streamers extending from the storm. These streamers, however, should seldom be individually visible except at the initiation of deepening, since the longer term production and diffusion of the cirriform clouds would cause most of the streamers to become obscured by the relatively uniform brightness of the canopy as a whole.

Figures 11-21 and 11-22 show examples of this feature for typhoon Karen on November 9 and 11, 1962. Figure 11-21 illustrates the actively deepening state. In Figure 11-22 deepening is still underway but a steady state of cirrus production and evaporation has been reached, and filling in of the canopy has obscured some of the streamers. While no exceptions to these observations have been noted, further study is necessary to fully confirm these tentative findings.

The geometric curvatures of these outflowing cirrus bands frequently parallel the inflowing, lower-level, convective bands. Since the differences in the two types of bands are basic to cloud pattern interpretations, hurricane bands should be unambiguously identified as to whether they appear to be of a cumuliform or cirriform nature.[8]

11.6 STORMS OF HURRICANE INTENSITY

At this stage in the life cycle of a tropical cyclone, the pictures clearly indicate the existence of a major storm at the surface. The main identifying features are: (a) significant increase in the organization and relative brightness of the cirriform canopy, (b) much of the lower tropospheric banding associated with the storm is obscured by a comparatively symmetrical cirriform canopy, and (c) symmetrical organization of the peripheral cumuliform bands. Figure 11-23 shows this stage of development of typhoon Ruth on August 15, 1962. Comparison with the August 14 example of Figure 11-17 reveals quite clearly the changes which have occurred, particularly the far more extensive cirrus canopy.[8]

Accordingly, further changes in intensity will only be evident in changes in the cirriform canopy, or at or beyond the periphery of the storm. It has been suggested that the extent and degree of the clear or minimum cloud area surrounding the storm (Fig. 11-1) may also increase with increasing storm intensity.[95] A severe tropical storm or hurricane influences the cloud organization to well beyond the associated cirrus shield, and one of the better subjective clues for estimating intensity may be the appearance, size and sharpness of the "organized" clear or

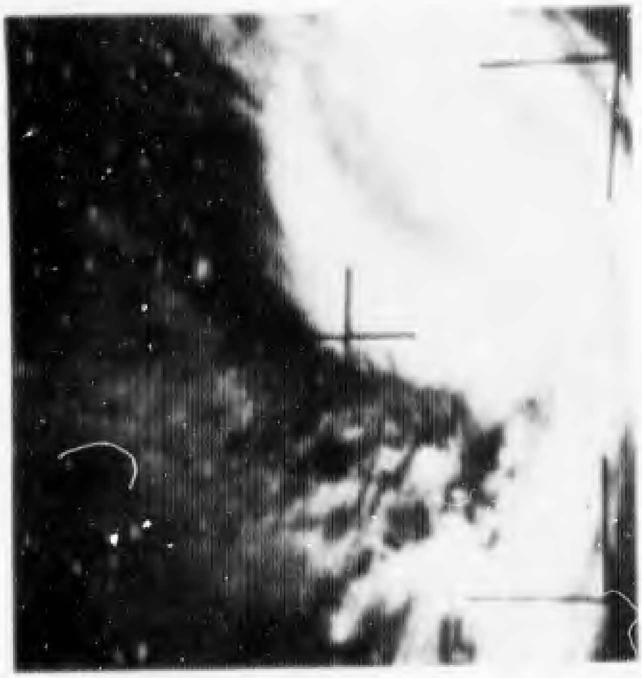


Fig. 11-22 Typhoon Karen, November 11, 1962

Fig. 11-23 Early Mature Typhoon, Typhoon Ruth, August 15, 1962

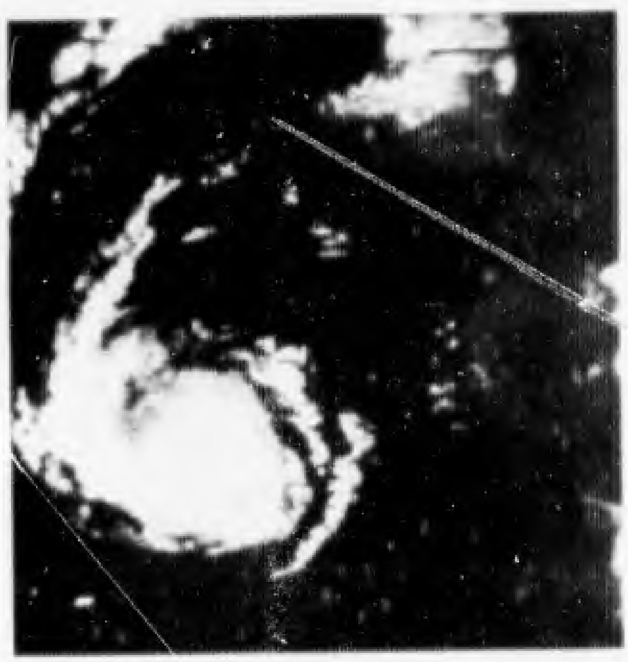


Fig. 11-24 Small Typhoon

minimum-cloud area on the periphery of the storm.[97]

Satellite observations may be of special value in detecting and tracking midget typhoons, sometimes known in Japan as "mame-Taifu." These storms, because of their small size (Fig. 11-24), are difficult to detect using only conventional observations; and they frequently move onto a coast with damaging winds.[95]

11.6.1 Cirriform Canopy Size as an Indicator of Storm Intensity

If the upper level outflow area of a hurricane is assumed to be approximately equal to the lower level inflow area (as conventional observations suggest), information about storm size and intensity can be inferred from the size of the cirriform canopy. Cirrus ice crystals have a long lifetime and so may travel several hundred miles before evaporating. The extent of the cirriform canopy may, therefore, provide a representation of the upper troposphere outflow and the intensity of the storm. Limited tests have so far tended to support this hypothesis (Fig. 11-25). It may, however, be possible to encounter an intense deepening storm with a relatively small cirriform canopy.[8]

The extreme variability of canopy size is indicated, for example, by a comparison of the overall sizes of typhoons Sarah and Karen of 1962, shown in Figures 11-24 and 11-22 respectively. Sarah was a relatively small storm with 20 kt winds within 60 miles of the center and no winds exceeding 100 kts within 20 miles of the center, while Karen approached the "super" category with 30-40 kt winds extending 300-400 miles from the center and winds exceeding 150 kts at 30 miles from the center.

After a hurricane reaches maximum intensity, reasonable care is necessary when relating the cloud shield size to storm intensity since the cloud shield can be conservative and highly persistent even though the hurricane may be weakening. For at least short periods after a hurricane degrades to tropical storm intensity, the cloud shield may remain as large as during the hurricane stage. Some loss of spiral character[95] and a decrease in brightness is often noted, however.

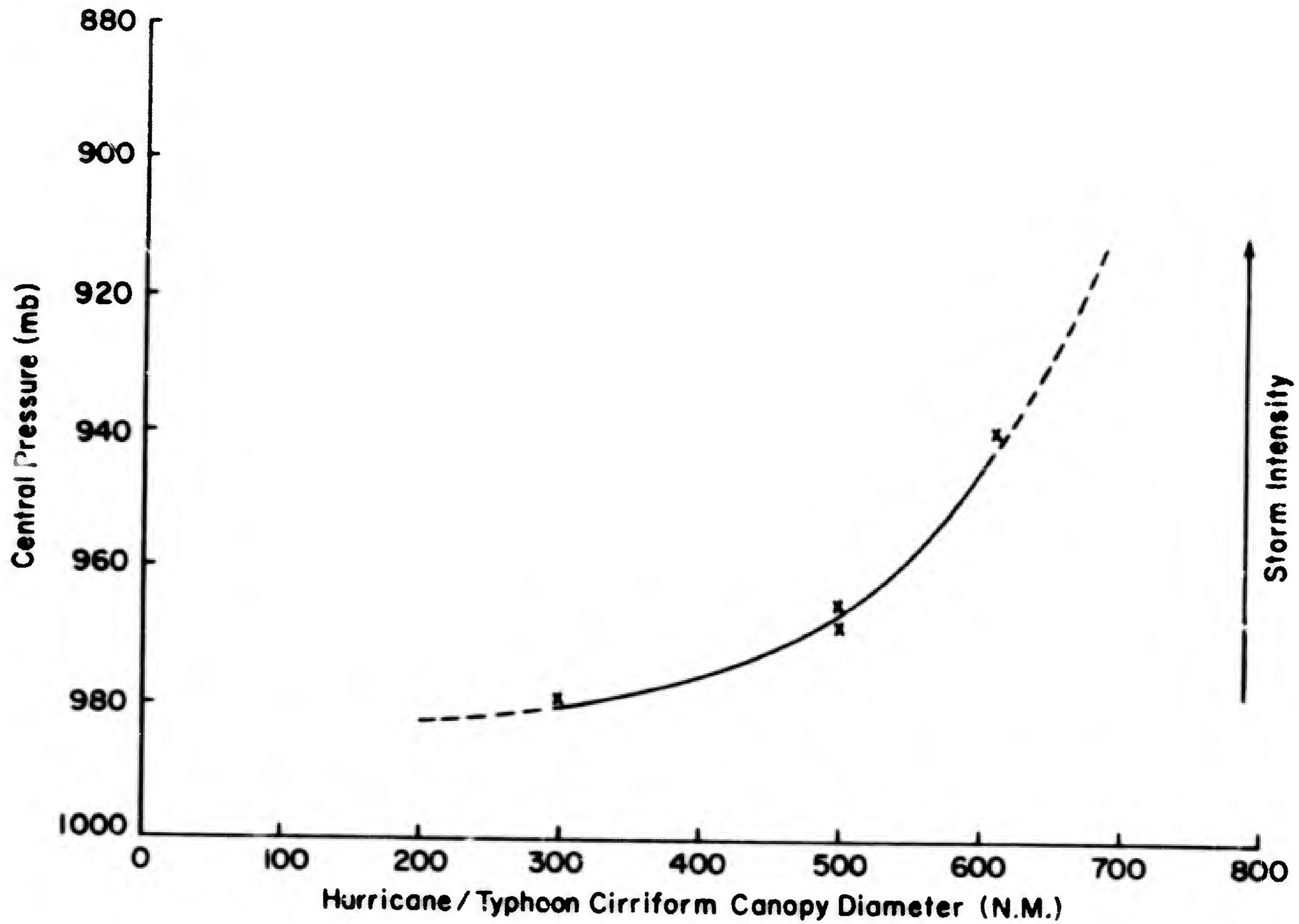


Fig. 11-25 Hurricane/Typhoon Cirriform Canopy Diameter Vs. Central Minimum Pressure

11.6.2 Areal Extent of Destructive Wind Speeds, and Distribution of Surface Winds

In several hurricanes, areas of more intense winds at lower levels (arbitrarily defined as areas with sustained wind speeds of 50 knots or greater) have been correlated with a bright cloud ring, or a doughnut-like amorphous cloud mass, surrounding the center of apparent circulation. Asymmetrical distributions of surface winds were found to be frequently correlated with asymmetrical cirriform canopies.[8] The selection of a sustained speed of 50 kts or greater as representing a destructive wind, while somewhat high for some operations, is low for many others and thus provides a compromise threshold.

11.6.2.1 Areas of Intense Winds

It is well known that the most intense winds are contained in the area only a short distance outside the ring of maximum convective activity associated with the wall clouds and in the more active regions of the spiral bands. If these areas can be identified in satellite photographs, a useful inference can be made as to the extent of the destructive winds.

In studies to date it has been found that, while positive identification of the major convective areas was not always possible, certain subtle characteristics do, at times, suggest differences between the convectively active areas and inactive areas. Figure 11-26, a photograph of typhoon Amy on September 3, 1962, illustrates this difference. Surface ship reports for several hours both before and after the time of this photograph show extensive areas of 40 kt winds in all quadrants of the storm at radial distances between 200 and 300 miles. Yet typhoon Amy was a vigorous storm with winds exceeding 100 kts near the center. It thus seems reasonable to assume that most of these high winds, say those in excess of 50 kts, were concentrated in the vicinity of the narrow bright cloud ring which appears to extend only approximately 30 miles around the "eye".[8]

In some cases a "bright" and apparently convective ring was not present in the area of anticipated high winds (in excess of 50 kts), but the area was still identifiable by a doughnut-like amorphous mass surrounding the center of apparent circulation. Figure 11-27 contains an example of this type of cloud pattern. The discontinuity in the cloud field which nearly surrounds the doughnut is also an identifiable characteristic of this feature.[8]

It has previously been noted that, in many hurricanes, there is a large outer area with wind speeds near 30 kts. This enormous peripheral circulation constitutes the main difference between large and small mature storms. Conditions in the core are quite similar.[91]

Additional support for this concept is provided by comparing the area of expected strong winds to the total storm area in several representative cases,[8] as shown in Table 11-1.

Table 11-1

Percentage Comparison Of Maximum Wind Area To Storm Area

Percentage of Total Area Occupied by Strong Winds	Storm Diameter
40	Small - 250 miles
20	Medium - 250-400 miles
10	Large - 400-700 miles

11.6.2.2 Asymmetrical Wind Distributions

In many Atlantic hurricanes severe weather extends farther to the right than to the left of the direction of motion, where it may end abruptly within 40 miles of the core.[91]

This and other similar observations, based on studies of conventional synoptic data, suggest that the asymmetrical cloud distributions seen in many satellite photographs of tropical vortices may be indicative of the asymmetrical wind speed distributions indicated above. There is, however, no known reason for these asymmetries to be restricted to the right front quadrant, although there tend to be more of these cases.

Examination of approximately 10 storms which showed an asymmetrical cloud distribution in satellite photographs has indicated that this relationship is valid, and that a marked asymmetry of surface wind speeds does occur beneath asymmetric cloud canopies. Figure 11-28 shows the asymmetrical cirriform shield of typhoon Opal on August 4, 1962. The cirriform shield on the east side is approximately three times as wide as that on the west. Figure 11-29 shows the wind field, as composited over the 48 hour period 1200Z August 3 - 1200Z August 5, relative to the

Fig. 11-26 "Bright Ring" Indicator of Maximum Wind Speed Area, Typhoon Amy

Fig. 11-27 "Doughnut" Indicator of Maximum Wind Speed Area, Typhoon Jean, November 8, 1962

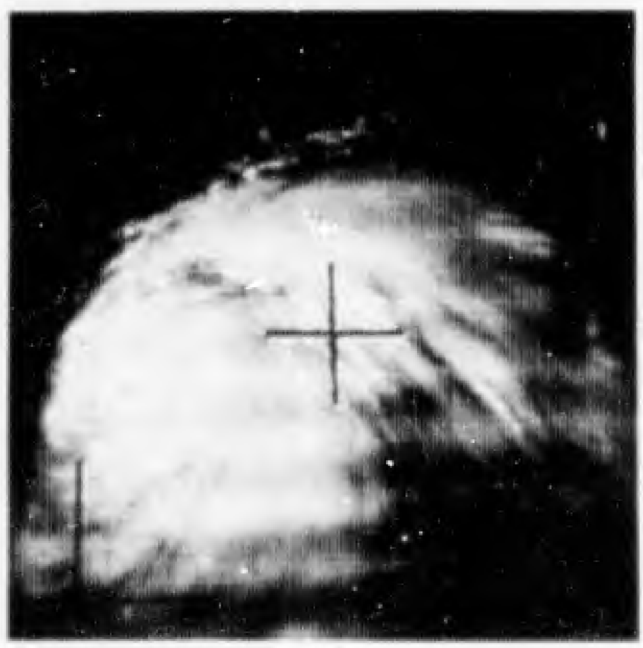


Fig. 11-28 Asymmetrical Cloud Distribution, Typhoon Opal

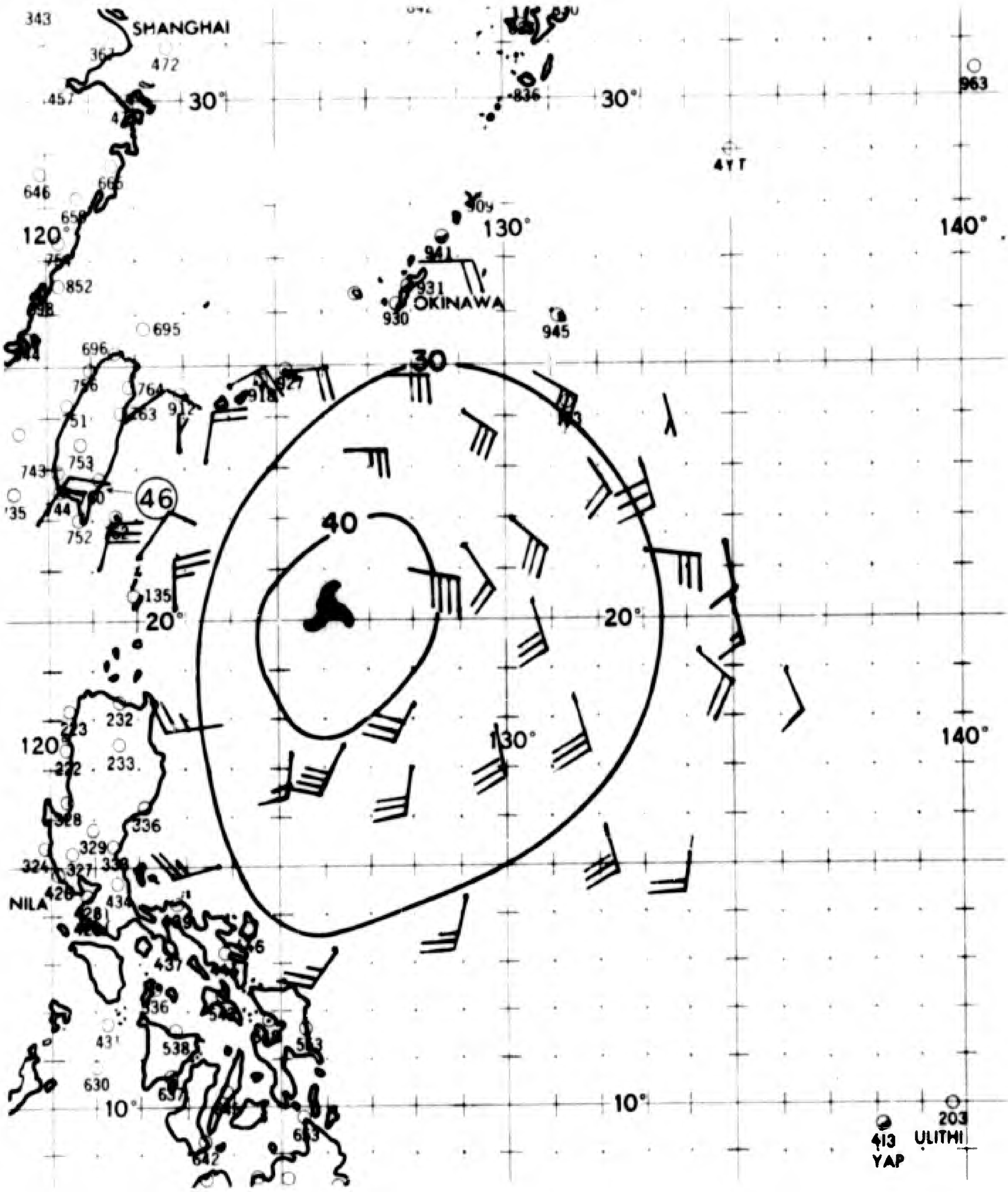


Fig. 11-29 Composite Surface Winds, August 3-5, 1962, Relative to Typhoon Opal (August 4)

center of Opal at picture time (0800Z August 4). The radius of 30 kt winds is approximately twice as great to the east of the storm center as it is in the direction of motion, toward the west.[8]

This concept appears valid for any quadrant where a relatively bright asymmetrical cloud shield is present. This information should be valuable when forecasting for marine interests.

11.6.3 Upper Tropospheric Flow Patterns Near Hurricanes

Upper level flow patterns can also be determined from cirriform streamers and the brightness or density gradients of the cirriform canopy previously discussed in Section 11.5.3. This again emphasizes the need for clear differentiation between these cirriform cloud patterns and lower level cumulus cloud bands.[8]

While primary interest in the wind field of tropical vortices is more normally in the surface layers, there is a requirement, from the point of view of numerical forecasting and aircraft navigation, for knowledge of the upper tropospheric wind direction and speed. Except for special reconnaissance flights and scattered radiosonde observations in the proximity of tropical storms, such wind data are seldom available. Previous observations suggest that cirrus radiate and move outward from the center of the tropical cyclone, and furthermore indicate that winds (and therefore the cirrus streamers) in the upper troposphere over and around mature tropical storms are characterized by numerous anticyclonic eddies whose centers are approximately 100 nautical miles from the "eye". The wind flow on the exterior of these anticyclonic cells is outward from the "eye".[60,115]

Satellite photographs provide considerable support for the above concepts.[8,31,33] The character and appearance of the cirriform clouds, i.e., thin and tenuous down wind and thick and dense upwind, appear to indicate the direction of the upper tropospheric winds. This is indicated by comparison of Figure 11-30, a picture of hurricane Daisy on October 5, 1962, with Figure 11-31 which shows the streamline analyses for 200 mb (39,000 ft). Notice the close agreement between the cirriform streamers on the right side of the cloud pattern in the picture and the corresponding streamline orientation. Again, the similar geometric shape of the outflowing cirrus streamers and the inflowing convective bands is evident.[8]

There may be a high-speed band of winds at upper elevations, curving anticyclonically and running tangential to the edge of the hurricane cloudiness. Maximum speeds appear to be attained along the northern and eastern edges of the storm

(Fig. 11-32), near the 250 mb level, where the horizontal temperature gradient is also strongest. Where this jet continues southward after running along the eastern edge of the storm, a trailing area of cirrus-producing, convective cloudiness may be formed (Fig. 11-33). This high level southward flow to the southeast of the storm may also initiate development of a secondary vortex trailing the original storm and beginning as an upper air disturbance (see Fig. 11-32 and Section 11. 12. 3). In some cases, development of this secondary may lead to a circulation of tropical storm intensity.[32]

11.6.4 Precursor Squall Lines and Storm Motion

Hurricane squall lines or pre-hurricane convective bands normally occur well in advance of the storm. These outer precipitation bands or squall lines are apparently a quasi-permanent feature in hurricanes which may persist in the same quadrant of the storm for many hours.[66]

Convective bands or squall lines exterior to the cirriform canopy have been quite noticeable in many satellite photographs. A persistence of these bands with regard to both geometric shape and quadrant seems to be indicated. They are most frequently observed in the two forward quadrants. Their orientation is often approximately perpendicular to the direction of motion. Figure 11-34 shows hurricane Daisy on October 4, 1962; notice the relationship between the bright, apparently convective banding and the indicated direction of motion.[8]

While this feature does not appear on all cases of tropical vortices, it does appear with sufficient regularity to indicate probable significance and to make it worthy of trial use.

These lines of intensified convection are separated from the storm proper by a relatively clear annular zone of subsidence which curves around the rim of the high cloud shield along much of its circumference (Figs. 11-20, -24, -34). An upper level shear line is often found over the precursor convective line, or in the forward part of the clear zone just to its rear.[32]

Tornadic activity, associated with hurricanes, has been shown to develop primarily in peripheral regions, possibly in association with the pre-hurricane squall lines or outer convective bands.[25] Satellite observations now permit views which show the location of these bands, over hundreds of miles, and qualitative estimates of relative intensity are certainly possible. It should be noted that conditions in the annular zone, adjacent to these bands, fulfill several of the pre-conditions for

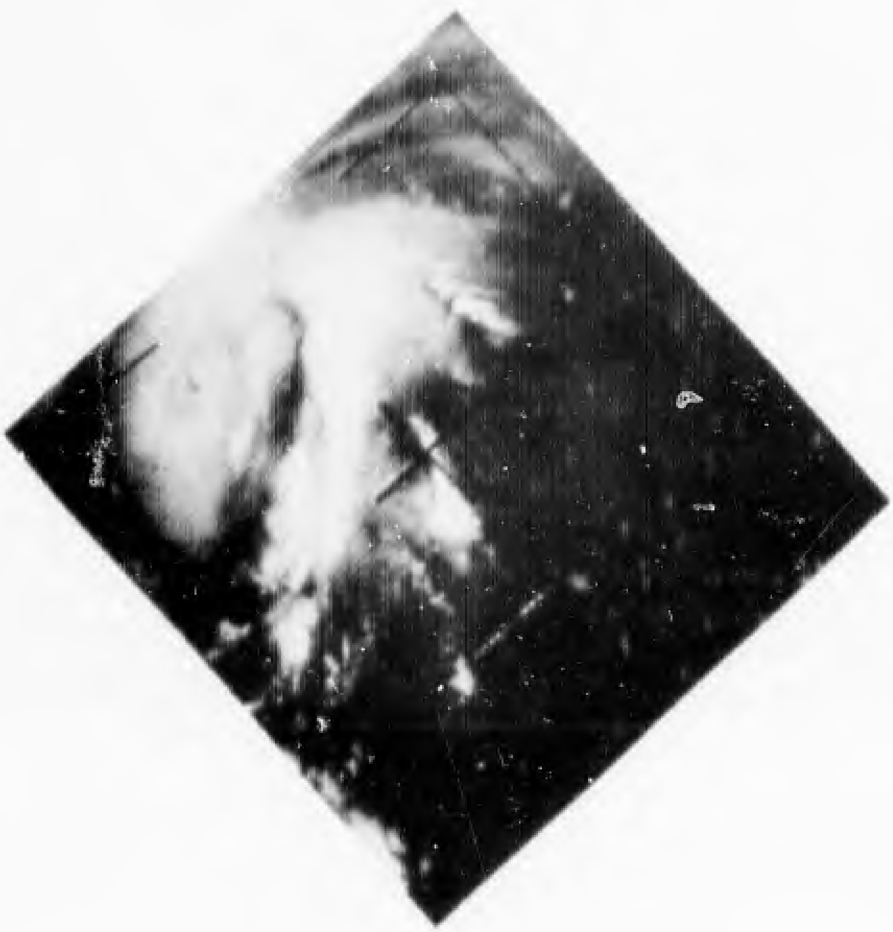


Fig. 11-30 Hurricane Daisy, October 5, 1962, Showing Cirriform Outflow Pattern

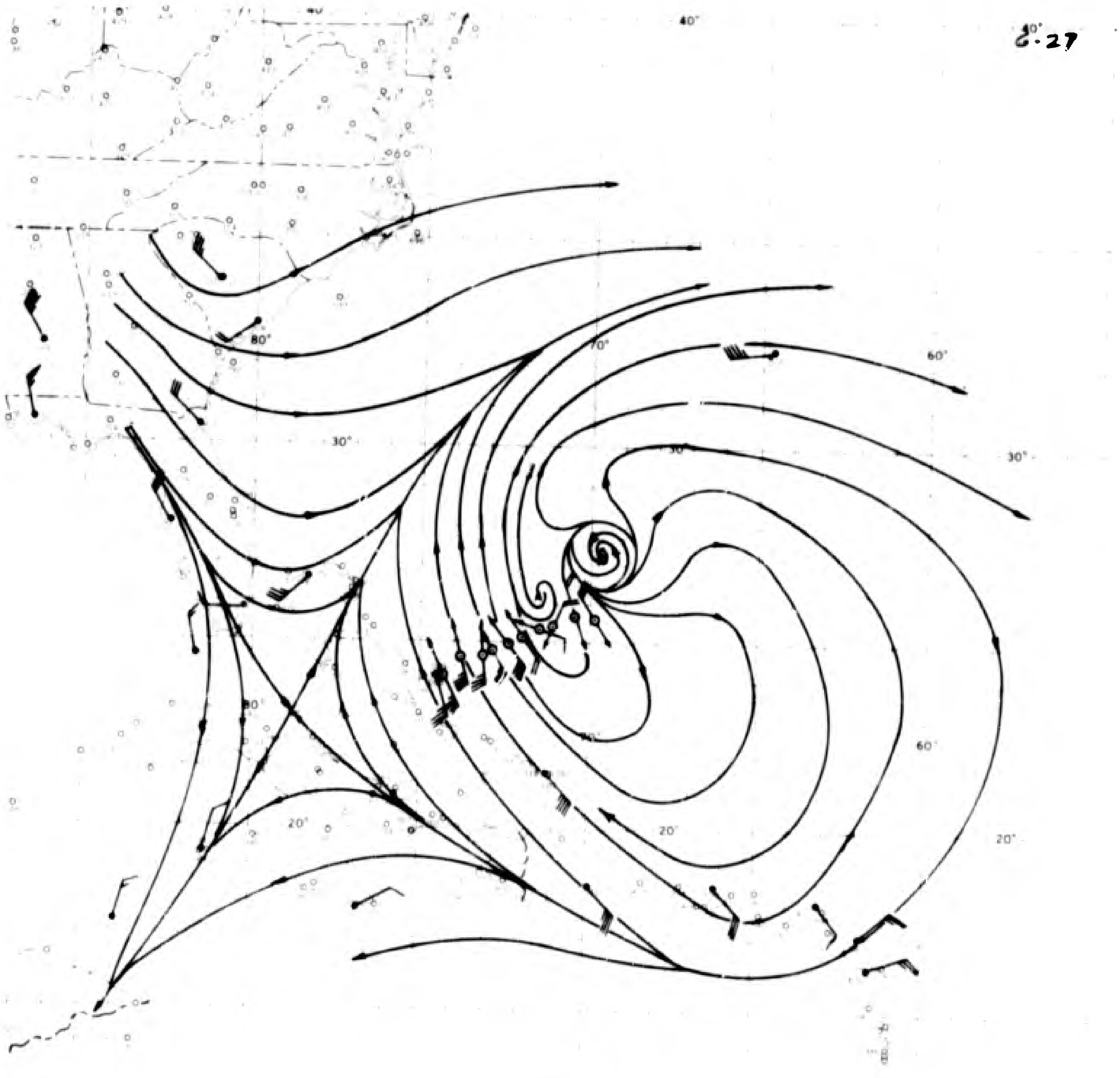


Fig. 11-31 200 mb Streamline Analysis, October 5, 1962, 1200Z

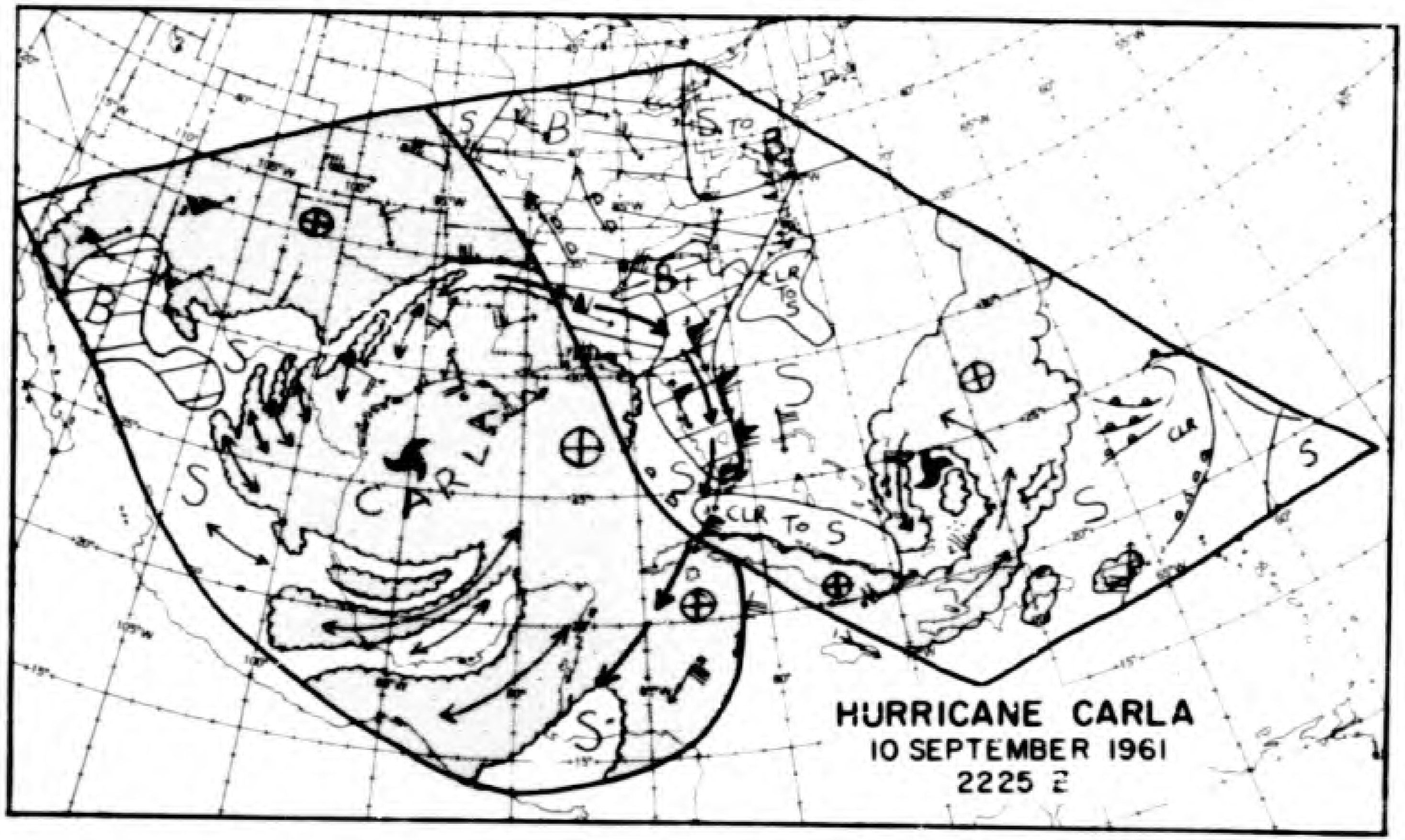


Fig. 11-32 A Composite TIROS III Nephanalysis, September 10, 1961 (from Reference 32).

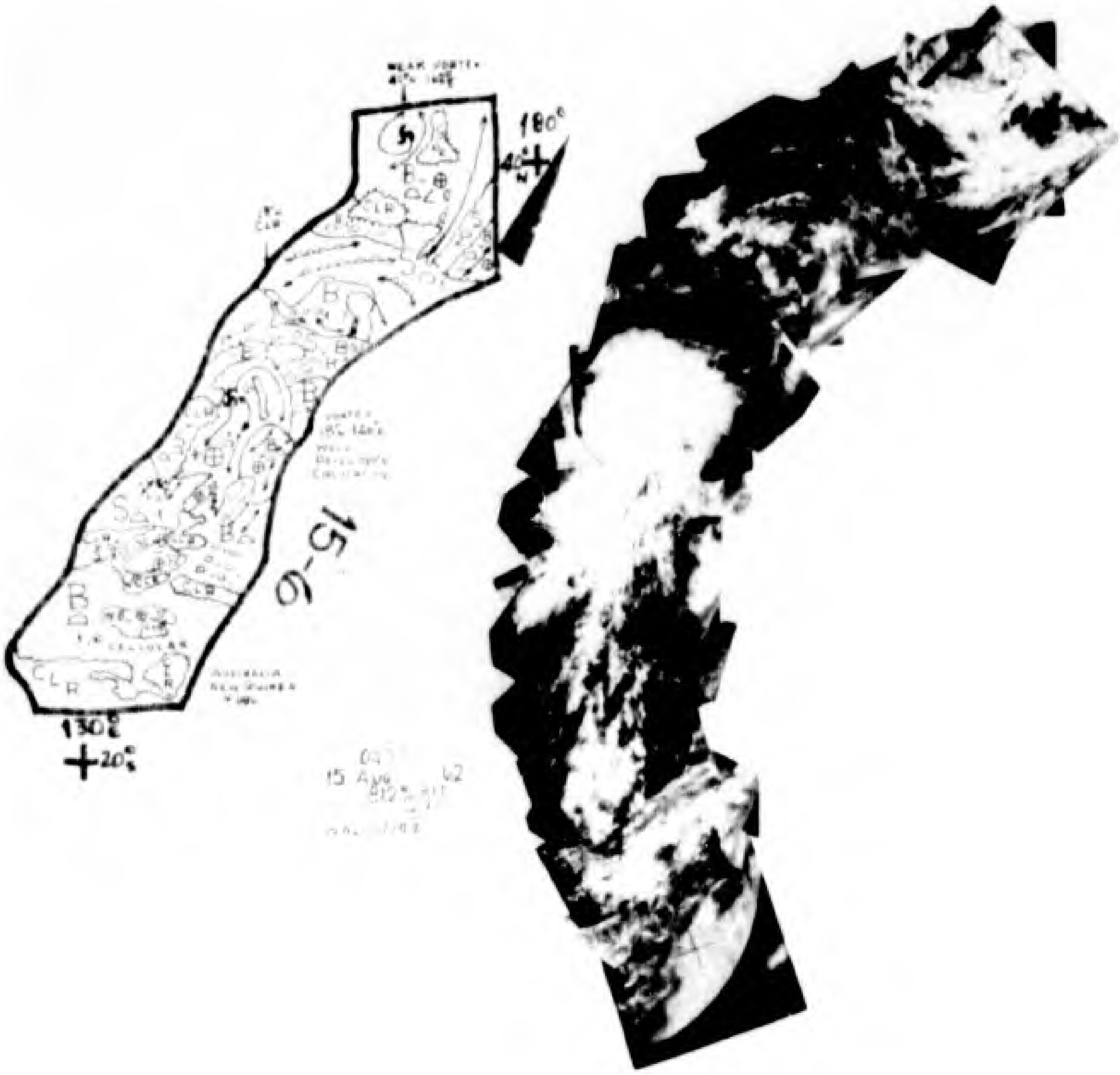


Fig. 11-33 Trailing Convective Cloudiness Equatorward of Typhoon Ruth (From Reference 32)

Fig. 11-34 Hurricane Squall Line, Daisy, October 4, 1962

Fig. 11-35 Well Defined "Eye", Beginning of Dissipation of Typhoon Ruth, August 18, 1962, 31N, 141E

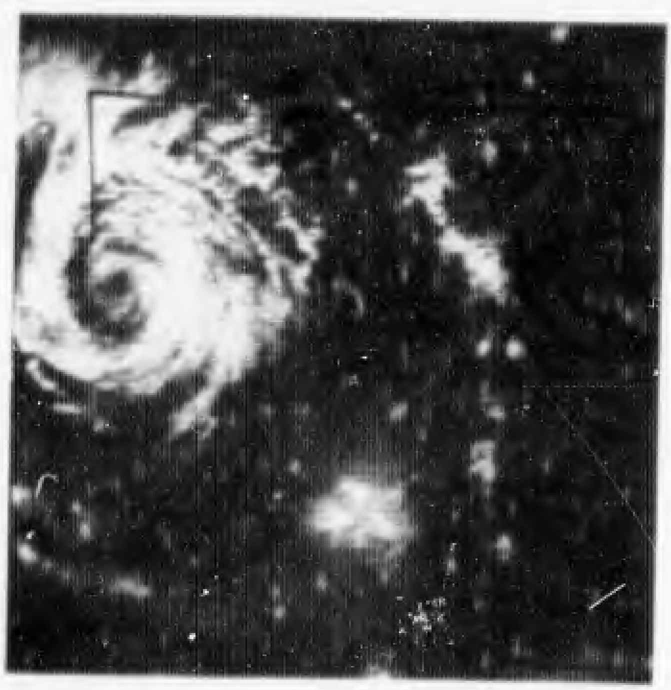


Fig. 11-36 Dissipating Tropical Storm Jean, November 13, 1962; 17.2N, 112E. Compare with Typhoon Jean, November 8, 1962 (Fig. 11-27)

Fig. 11-37 Typhoon Thelma, August 25, 1962; 29.5N, 136E

tornado development listed by Fawbush and Miller.[30] Among these are: (1) a low-level temperature inversion; (2) sharp vertical moisture stratification; and (3) a narrow band of strong winds aloft.[32]

The satellite observations can also, of course, provide information as to the width of the clear zone between the precursor squall line and the hurricane proper, and the extent of cloud cover within it (Fig. 11-34).

A tendency for the wider portion of the asymmetrical cloud canopy to occur above the area of highest surface winds, often to the right side relative to the storm motion, also provides a potential for determining future storm motion. When used with other indicators and techniques for determining direction, the combination may provide a more reliable estimate than any one technique used by itself. In the photograph of hurricane Daisy in Figure 11-34, for instance, the asymmetrical portion of the cirriform canopy lies to the right of the direction of motion, and therefore tends to support the direction of motion inferred from the location and orientation of the precursor convective band.[8]

11.7 DISSIPATING HURRICANES

The existence of several modes of decay for tropical cyclones precludes definition of a single characteristic pattern for this stage. There is, however, a tendency towards two types of decay patterns. These patterns are associated with (1) decay over tropical oceans, and (2) decay in mid-latitudes resulting from the intrusion of cold air or passage over land.

11.7.1 Dissipation Over the Ocean

In the hurricane which decays over water, a rather symmetrical, orderly change usually occurs. The cirriform canopy thins and may even dissipate in some quadrants. Figures 11-23 and 11-35 show an example of this decay process. The key features are continued existence of a well-defined "eye" (Fig. 11-35), but definite dissolution of a visible cirriform canopy.[8] This decay pattern has also been noticed in the eastern Pacific, where, when storms move under the vertical shear of an upper tropical ridge and an area of upper level southwest winds, the thick cirrus shield which has been over the core of the storm either completely dissipates (Fig. 11-36) or is blown to the east of the storm proper. Remaining wall clouds of the eye and/or close in lower-level spiral cumulus clouds may or may not still be visible.[97]

The usual sequence of decay over the open ocean indicates the need for using continuity to reliably determine the stage of development of a tropical storm, because of frequent pattern symmetry about the most vigorous stage.[8]

11.7.2 Dissipation Over Land

When the decay process is over land, much more rapid and marked changes occur.[8] The size and shape of the cloud mass may be altered when a portion of the storm circulation is orographically influenced.

An example of decay over land is shown in Figures 11-37 and 11-38. Figure 11-37 shows typhoon Thelma on August 25, 1962, when it was a medium sized, fairly intense typhoon, while Figure 11-38 vividly shows the changes which resulted from two days passage over the rugged Japanese Islands. Note the apparent continued existence of an "eye" in spite of definite breaking up of the remainder of the cloud pattern.[8]

In one case, terrain effects of an island appeared to produce a relatively clear notch in the northern boundary of a storm (Fig. 11-39). Apparently either cirrus formerly over this area of the storm produced by convective clouds was dissipated by the terrain, or, alternatively, the cirriform cloudiness, while thick enough to reduce the contrast of lower level cloud bands below the point where they can be discerned, was not thick enough to be visible by itself against a background of land.[31]

11.8 A MODEL OF TROPICAL CYCLONE DEVELOPMENT

The tropical cyclone development model proposed here can be separated into two distinct gross stages, which are in turn sub-divided into a total of six substages. The two gross stages divide the development sequence into a cold core stage* (banded cloud patterns with no major cirriform canopy) and a warm core stage* (banded, but with a well defined cirriform canopy). Within the cold core stage there are three substages: (1) disturbed convergent band with apparent cyclonic motion

* For a fuller discussion of cold core and warm core tropical systems, see Yanai, M., 1964: "Formation of Tropical Cyclones," Reviews of Geophysics, 2 (2), pp. 367-414.

Fig. 11-38 Decaying Storm Thelma, August 27, 1962, 41N, 139.5E

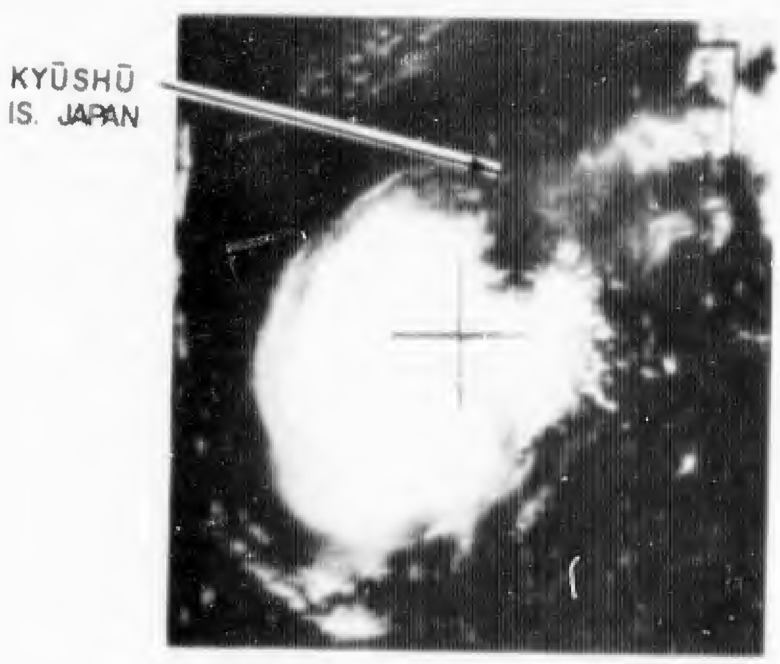


Fig. 11-39 Terrain Effects on Typhoon Sarah

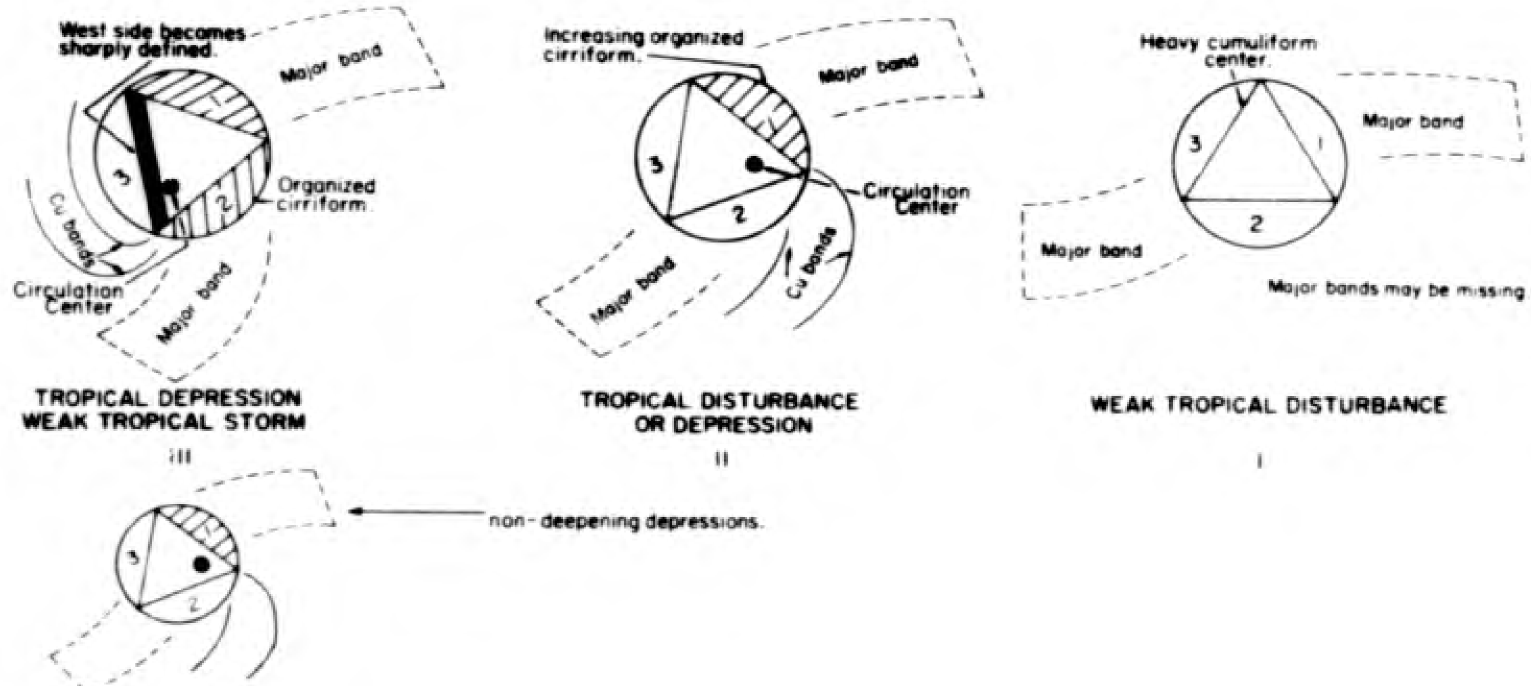


Fig. 11-40 Cold Core Stage of Tropical Cyclone Development

Fig. 11-41 Warm Core Stage of Tropical Cyclone Development

(Tropical Disturbance) (Fig. 11-6), (2) ill-defined vortex with prominent convergent bands (Tropical Depression) (Fig. 11-15), and (3) well defined vortex with banding still visible over most of the area (Weak Tropical Storm) (Fig. 11-16). In the warm core stage there are also three substages; (1) well defined vortex with organized cirriform cloudiness visible over most areas (Intense Tropical Storm) (Fig. 11-17), (2) well defined vortex with extensive cirriform canopy (Hurricane or Typhoon) (Fig. 11-19), and (3) well defined vortex but with some decrease evident in cirriform canopy (Hurricane or Typhoon decaying over ocean area) (Fig. 11-36).[8,75]

Physically, this model is based on the assumptions that the intensity of a tropical storm is related to:[75]

1. The amount of inflow of air into the storm in the lower troposphere, and that this inflow can be deduced from satellite observations through the cirriform cloudiness associated with corresponding upper troposphere outflow.

2. The amount and organization of heavy, convective cumuliform cells within the storm, which are directly visible from a satellite prior to formation of an extensive cirriform canopy and implied by continued persistence of a dense cirriform canopy.

The features and processes discussed in Sections 11.1 and 11.3 - 11.7, inclusive, as they pertain to the tropical cyclone development sequence, can be summarized in the symbolic model[75] presented in Figure 11-40 for the cold core stage and in Figure 11-41 for the warm core stage.

In these figures, the shaded central triangle represents the bright, heavy central cumuliform cloud mass. A triangle is used because this cloud mass is sometimes approximately triangular in shape, and especially because this symbolism is convenient for distinguishing three significant surrounding numbered areas. The numbered areas (1, 2, 3) represent the areas roughly:

1. To the northeast, or to the right rear relative to the direction of storm motion, of the central cloud mass.

2. To the south, or to the left, of the central mass.

3. To the west, or forward, of the central mass.

They are numbered in the order in which they most frequently become filled with organized cirriform cloudiness. These areas are hatched in those stages where they usually have significant, organized cirriform cloudiness.

The major cloud band, when the storm forms from one and so it is present, is indicated by the dashed, quasi-rectangular outline. Lesser cumuliform cloud bands spiralling into the circulation center are denoted by solid lines. Other key features are annotated on the schematics in Figures 11-40 and 11-41.

This model was developed under the sponsorship of the Air Force Cambridge Research Laboratories using observations obtained by TIROS in the major tropical cyclogenetic areas of the globe. There may be other development sequences which are not related to this model, such as those which occur in response to upper level disturbances. These will be considered, to the extent a basis is available from studies to date, in Section 11.10.

11.9 SECONDARIES TO TROPICAL STORMS

Secondary vortices have been noted in several cases in association with the tropical storm or hurricane stages of development. There are also some indications that these secondaries, in the form of heavy cumuliform masses, may also be connected with the tropical disturbance development stage.[8]

These secondaries appear to be most frequently observed in the eastern Pacific, although a few have been noted northeast of the Philippines and in the Atlantic.[32] Possibly similar secondaries are considered a common phenomenon by forecasters in the Pacific, who have thought of them as some type of wave formation.

The diameters of these secondaries are typically about 50 percent that of the primary. Their development, motion and dissipation seem to be closely governed by that of the primary. Separation from the primary is typically about 800 miles, with a tendency for reduced separation with increase in intensity. The most frequently observed location is south or west of the primary (Fig. 11-48), but this is not consistent.[8] A major cloud band often links the two systems together in a manner similar to the Debbie-Esther pair of 1961 (Fig. 11-42).

The formation of such secondaries in the upper air to the rear of a hurricane, as a result of a high speed southward moving current to the east of the primary storm,[32] has already been discussed in Section 11.6.3 (Fig. 11-32). In some cases, the circulation may penetrate to lower levels and develop into a full tropical storm. When secondaries form in this way, the linking cloud band is usually present.

In the eastern North Pacific, these secondaries appear to be weaker vortices which remain in and track along monsoonal trough lines (Fig. 11-8a), while those vortices which do intensify usually move to the north-west (Fig. 11-48) and out of the trough line.[96]

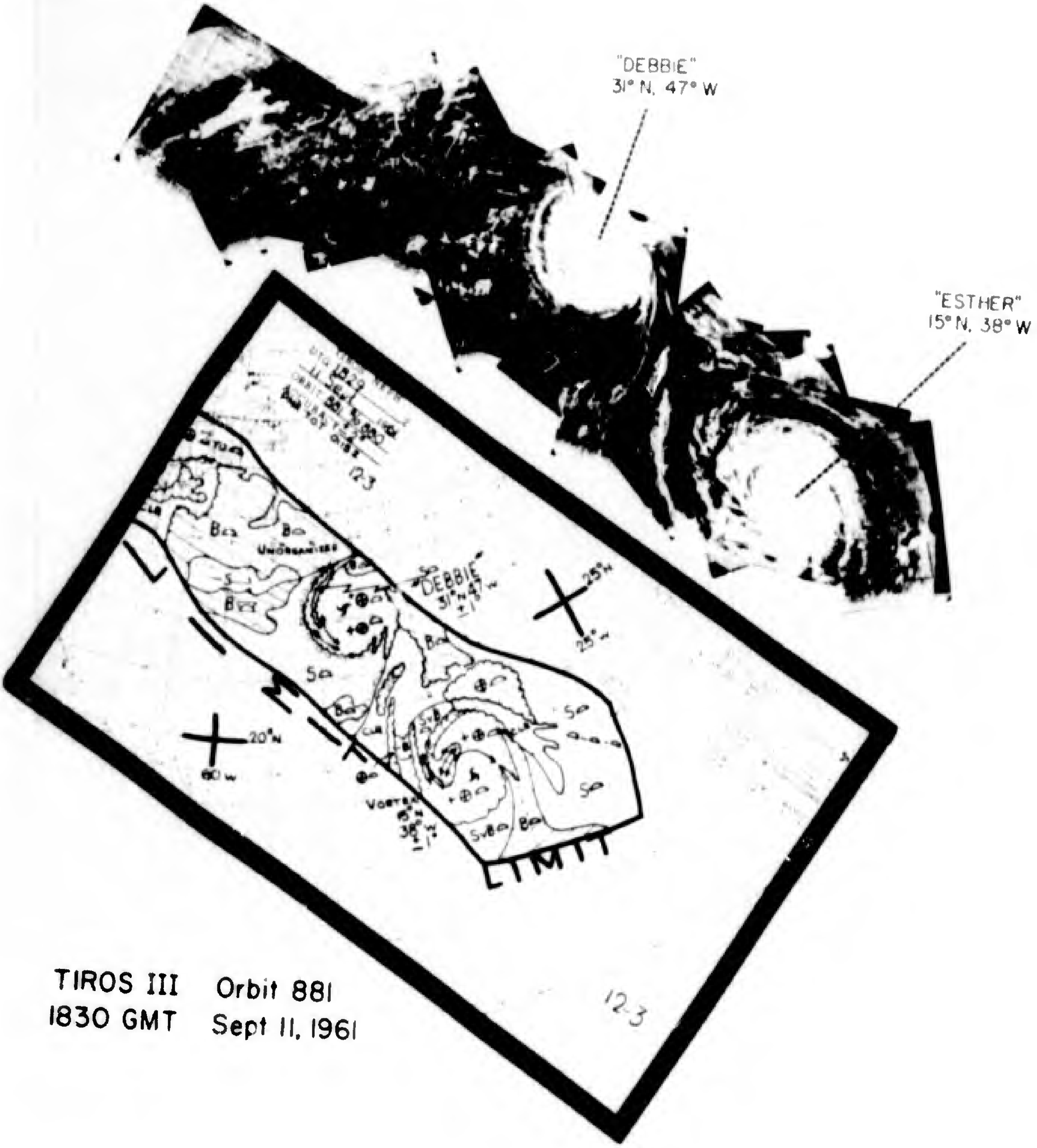


Fig. 11-42 Nephanalysis and Mosaic of Pictures on September 11, 1961, Showing Hurricanes Debbie and Esther

11.10 UPPER AIR TROPICAL SYSTEMS

In addition to tropical cloud masses and vortices associated with low level storms (including those of hurricane intensity), easterly perturbations, and mid-tropospheric developments, there are situations when similar appearing cloud patterns are associated with intense cells in the upper troposphere. In general, these upper level disturbances have a more "blob"-like appearance than those at lower levels (Fig. 11-43). These upper-level disturbances may at times induce surface weather conditions much like those normally associated with easterly waves and perturbations.

The more frequent relationship between these systems and the Pacific upper tropospheric trough system (Fig. 11-43b) may imply these systems are of more importance in the tropical Pacific than in the tropical Atlantic.[8] At least one such case in the Gulf of Mexico (Fig. 11-9b) has, however, been observed and studied.[19,94]

Unfortunately, at present there are often no definitive ways of determining the heights of such systems and so of identifying them from the satellite picture data alone.[34] In at least one such case* the satellite nephanalysis implied a surface cyclone which turned out to be an upper level cell (Fig. 11-44, -51d) over a surface anticyclone. This shows vividly that satellite data are often not sufficient within themselves, but must be used, wherever possible, in conjunction with proper tropical synoptic charts and a knowledge of regional climatology.[94]

A subjective screening of satellite photographs of such upper level systems associated with the North Pacific upper level trough suggests at least two regionally distinctive cloud patterns:[94]

Those vortices located on the northeastern end of the trough, poleward of 30°N, between Hawaii and the western United States do not have the massive cirrus shield. Although these vortices are located over the highest surface pressure, their circulations penetrate deep into the lower layers and organize the low and middle clouds into vortex patterns which are apt to be misinterpreted, in the absence of synoptic charts, as belonging to surface storm systems. One example is shown in Figure 11-45. Figure 11-46 shows another example located at 38°N 137°W. This cloud pattern could easily be misinterpreted as belonging to a large decaying surface cyclone of the mid-latitudes.

* Which will be used in Section 11.12.3 to illustrate tropical analysis procedures; see Figure 11-51a.

Fig. 11-43a Satellite View of the Cloud Mass Associated with the Upper Level Vortex Located at 22°N, 162°W from TIROS III Orbit 696. System is Identified on Figure 11-43b as N.

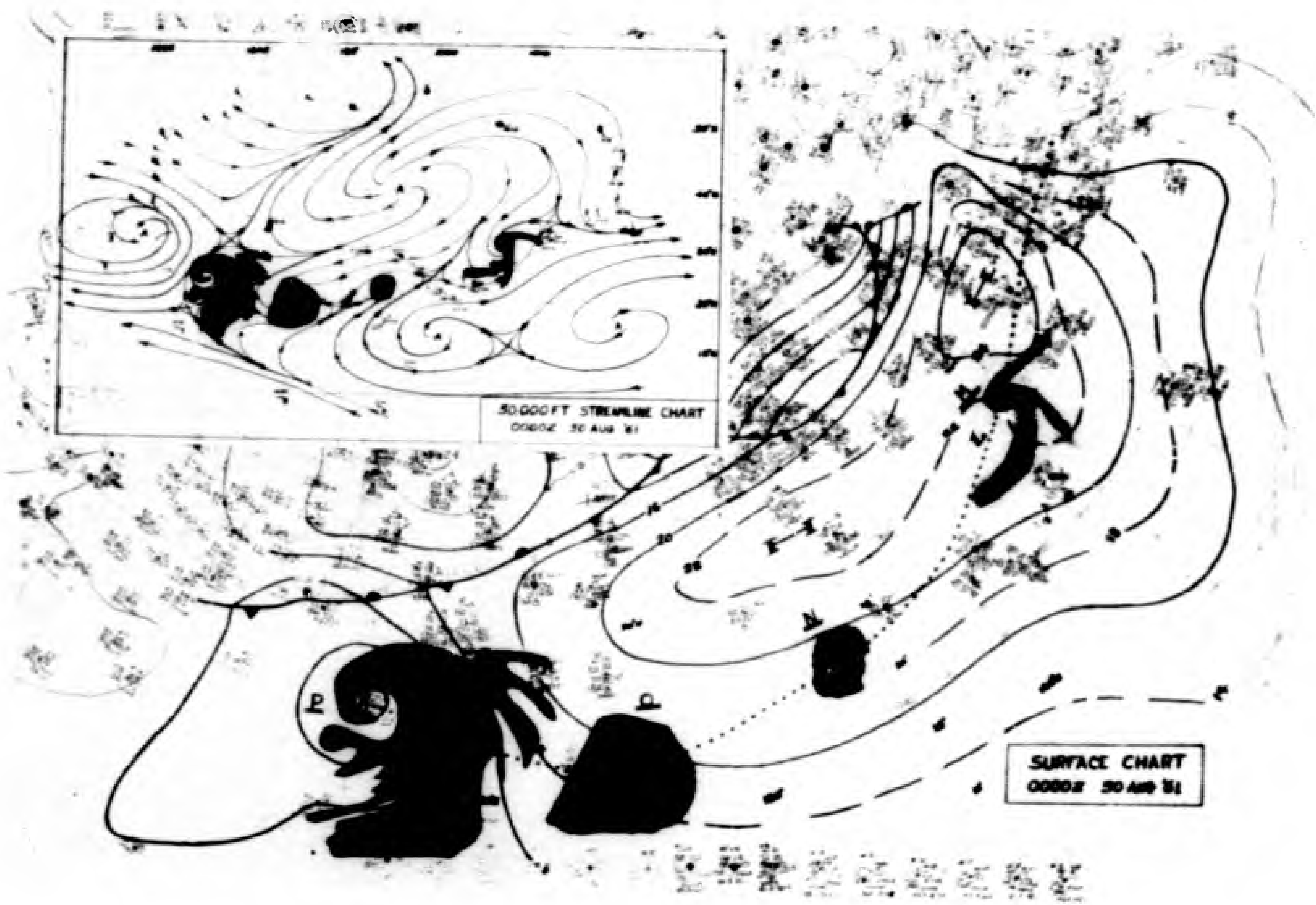


Fig. 11-43b Surface Pressure Analysis and 30,000 ft Streamline Analysis for 0000 GMT, 30 August 1961. Upper Troposphere Trough Denoted on Surface Chart by Dotted Line. Shaded Areas were Extracted from the Transmitted TIROS III Nephanalyses (From Reference 94)

Fig. 11-44 Cloud Pattern Associated with Upper Level Cell Over Surface Anticyclone

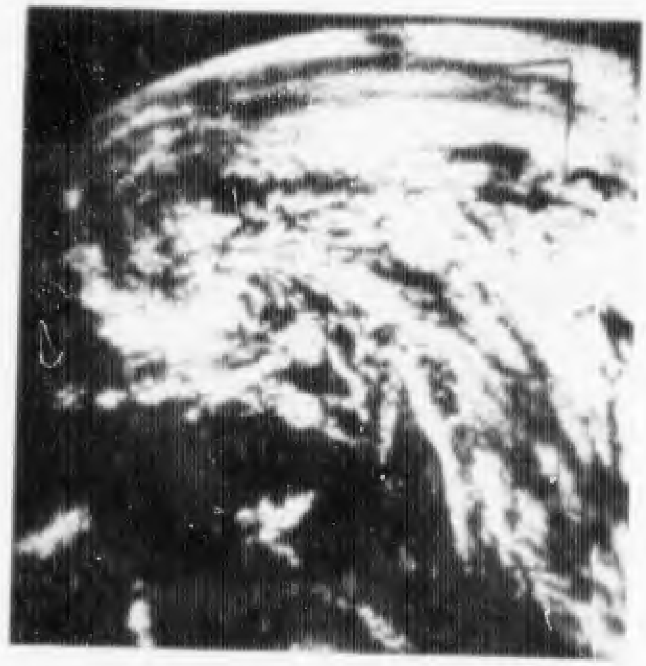


Fig. 11-45 Cloud Mass Associated with Upper Level Vortex from TIROS III. System is Identified on Figure 11-43b as M

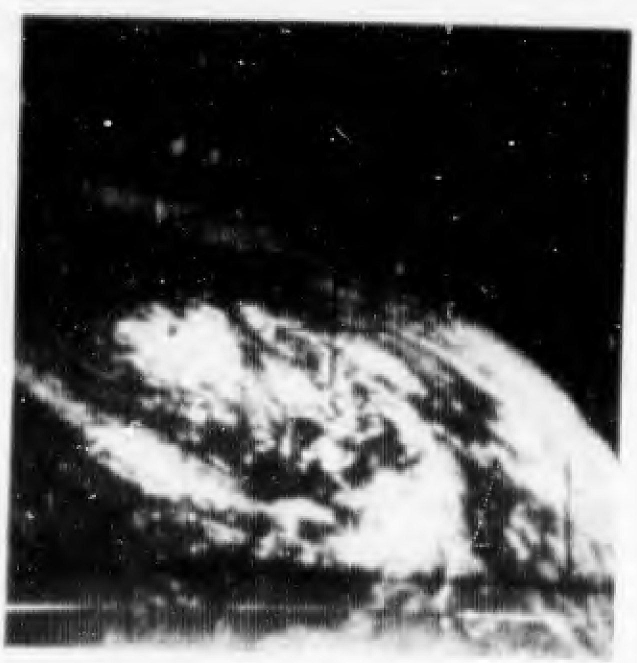


Fig. 11-46 TIROS III Photograph of Upper Level Vortex

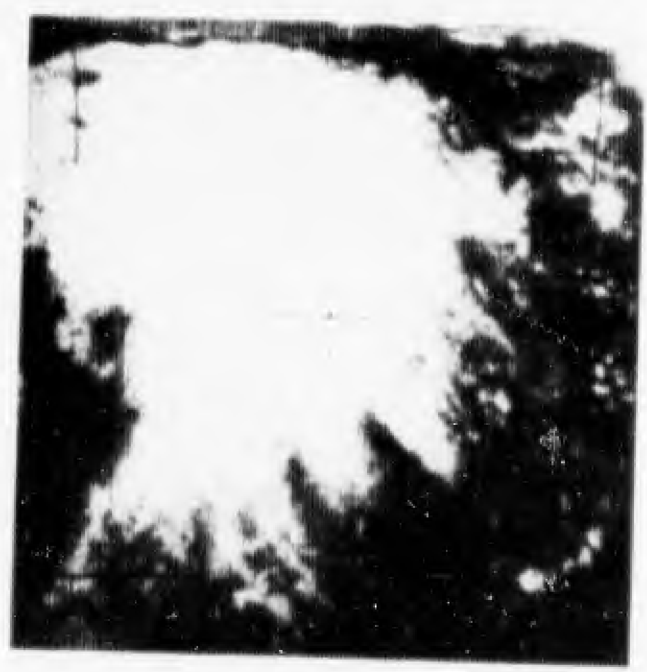


Fig. 11-47 TIROS III Photograph of Upper Level Vortex

Those vortices, located along the central western portion of the trough, equatorward of $25^{\circ}N$, have a massive shield of alto and cirrus clouds. Most do not exhibit a vortex pattern in the upper shield, nor do they penetrate sufficiently into the lower layers to organize the cumulus. This is fortunate, for with more spiral organization, they would likely be misinterpreted as severe tropical storms or hurricanes. A typical example is shown in Figure 11-47.

It appears that tropical cyclones which form in the eastern North Pacific monsoonal trough and move far west at low latitudes may, in a considerable number of cases, be unable to maintain a vortex circulation at or near the surface (Fig. 11-48). They can, however, survive as vortices at levels in the lower troposphere above the surface and retain a cloud structure which can be identified in satellite photographs.[96]

11.11 GEOGRAPHICAL LOCATION OF TROPICAL STORMS

As discussed in Section 2.2.1, errors in the geographical locations of features seen in TIROS pictures should (except near the horizon) seldom be as great as 2° of latitude, and that they are more frequently of the order of 1°.

Analyses of data for 1961, 1962 and 1963 hurricane and typhoon cases indicate the following experience (see Table 11-2) as to errors in satellite positions of hurricane centers with the "true" positions being taken as those established by weather reconnaissance aircraft.[8, 57]

Table 11-2

Tropical Vortex Location Errors

Percentage	Position Error (n. miles)
50	$\leqslant 50$
75	$\leqslant 75$
90	$\leqslant 115$
99	$\leqslant 160$

Geometric features of the cloud patterns, such as the eye or inward extension of the bands, are usually adequate to identify the circulation center, with position errors in excess of 100 nautical miles unlikely. In cases where an "eye" is present, the center of apparent circulation is instantly located.

Fig. 11-48a With Secondary

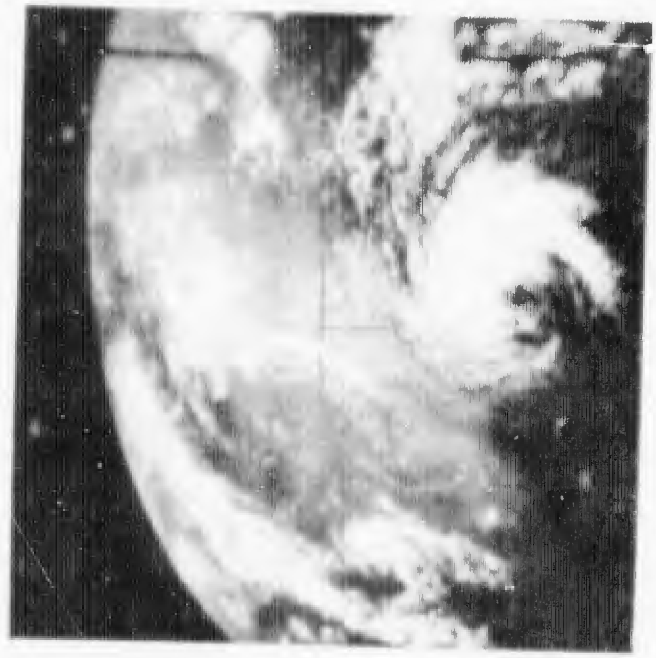


Fig. 11-48b Decaying

Fig. 11-48 Eastern North Pacific Tropical Cyclone

Fig. 11-49 Use of Spiral Bands to Determine the Center of Circulation

Figures 11-19, -35, -36 show examples which have a well marked "eye". When such a vortex is also near the center of the photograph there is no reason to expect the location error to exceed one degree of latitude. When there is no clearly defined "eye", orientation of the spiral cloud bands should provide an excellent indication of the apparent circulation center. This is accomplished by extending the spiral cumuliform bands inward, maintaining the indicated rate of increase in curvature, until a number of intersections occur. The circulation center will be located by these intersections. Figure 11-49 shows an example of this procedure in connection with hurricane Daisy. The center of apparent circulation obtained in this way compares favorably with that defined by an "eye", and there should be little question as to where the center is located. There is seldom any need to resort to use of the geometric center of the cloud mass as the center of circulation; frequent asymmetry of tropical storm cloud patterns, previously discussed, makes this undesirable except as a last resort.[8]

11.12 TROPICAL ANALYSIS PROCEDURES*

This section presents a specific case study to illustrate some of the ways satellite observations can aid in solving a tropical analysis problem.

11.12.1 A Brief Review of Tropical Circulations

Because of the nature of the case to be considered, it seems desirable to recall that the tropical atmosphere is divided into two, or possibly three, unique flow layers. The lowest layer, near the surface, is that of the easterly trade winds which occasionally contain imbedded waves or vortex perturbations. The upper layer, near the 200 mb level, contains numerous transient anticyclones and cyclones. As previously mentioned in Section 11.4, recent evidence[74] suggests a third unique layer which is centered near 600 mb. Areas of extensive cloud cover and associated poor weather may be produced by perturbations within any of these layers.

The tropical forecaster frequently finds that satellite observations reveal perturbations of major proportions which are not evident from surface or lower tropospheric analyses of conventional observations, even in areas where conventional data coverage would, in the tropics, be considered good.

* Section 11.12 was prepared by Mr. Earl S. Merritt

11.12.2 Analysis Techniques

The general procedures which should be followed to integrate satellite observations into an analysis routine have been discussed in Chapter 10. These procedures are applicable to tropical areas with only minor revision. Perhaps the major difference results from the fact that the orbital period of the TIROS series of meteorological satellites usually leaves about a ten degree longitude gap between nephanalyses at the equator, as can be seen, for example, in Figure 11-50.

Accordingly, compositing of adjacent orbits along the lines discussed in Chapter 10, while still advisable, will not be as useful as in more poleward latitudes. While the extratropical analyst usually can directly observe continuity of cloud patterns between adjacent nephs, the tropical analyst must interpolate between orbits, inferring an appropriate continuity, where it appears applicable, from the features in those areas that were covered by the satellite observations as supplemented by other data and by synoptic and climatological experience. These problems may not be totally obviated by the Wheel TIROS or Nimbus.

While present nephanalysis procedures provide considerably more detail than those operationally disseminated prior to 1964, and while this detail is useful in some instances, it still is often insufficient for many mesoscale aspects of tropical analysis which can be accomplished when photographs are directly available, as from an APT facility. Thus one frequently finds a gross depiction of the overall pattern of covered and mostly covered areas to be nearly as useful, for routine analysis, as detailed nephanalyses. The following example of a tropical analysis problem has used this concept of gross depiction of the cloud-pattern.

11.12.3 An Illustrative Example*

On September 9, 1961, the TIROS nephanalyses showed a peculiar hook shaped cloud mass centered near 23N, 72W. Figure 11-51a shows this pattern superimposed on the low level streamline analysis. Note the lack of any obvious correspondence between the cloud pattern and the low level analysis. Figure 11-51b shows a similar comparison at 700 mb and the very limited correspondence between the two patterns at this level. When we compare the cloud pattern to the 500 mb

* This case has also been studied by Frank[33] in a concurrent, independent analysis.

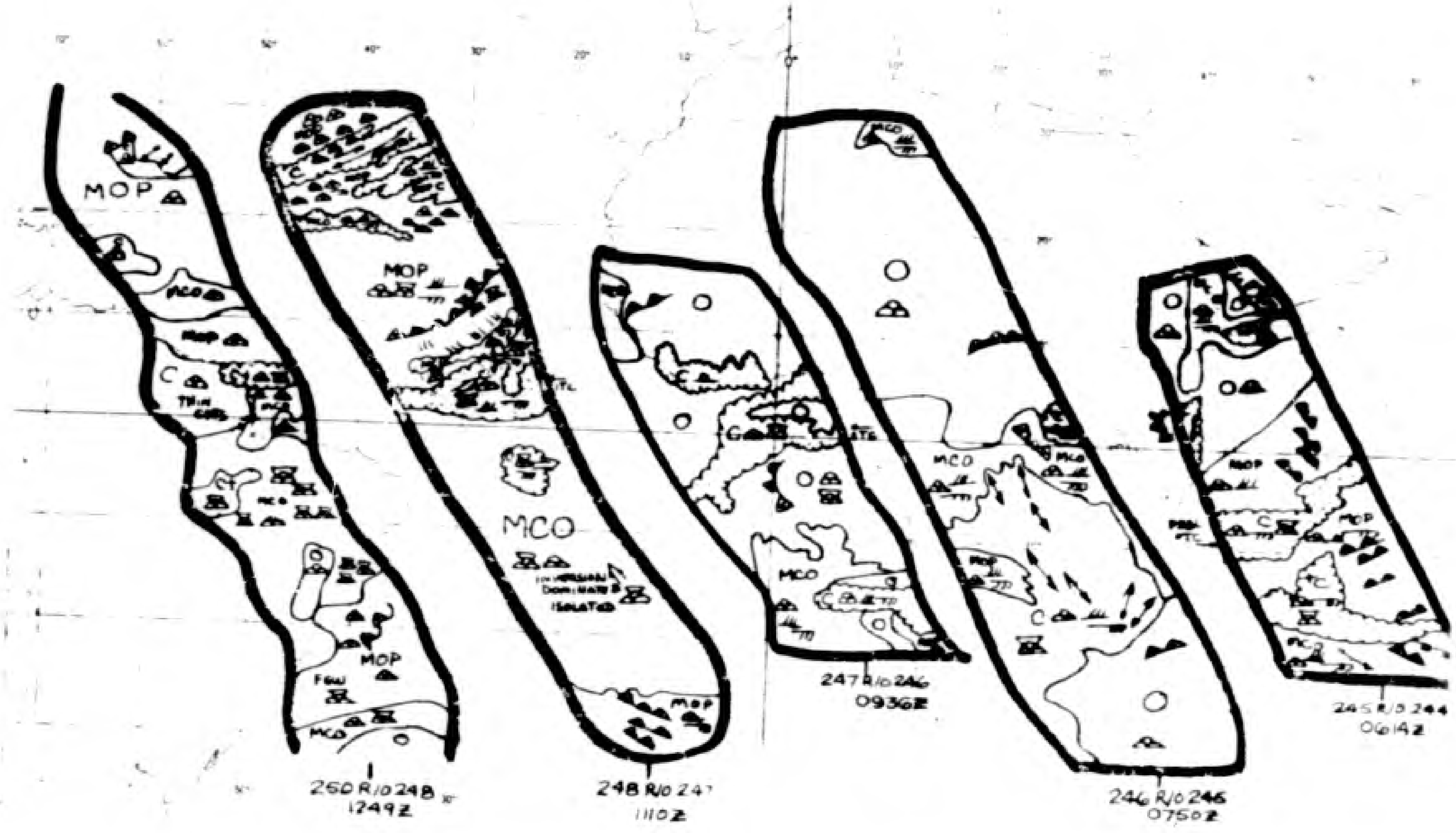


Fig. 11-50 Neph Mosaic for Tropical Region Showing the Gaps in Satellite Coverage Near the Equator

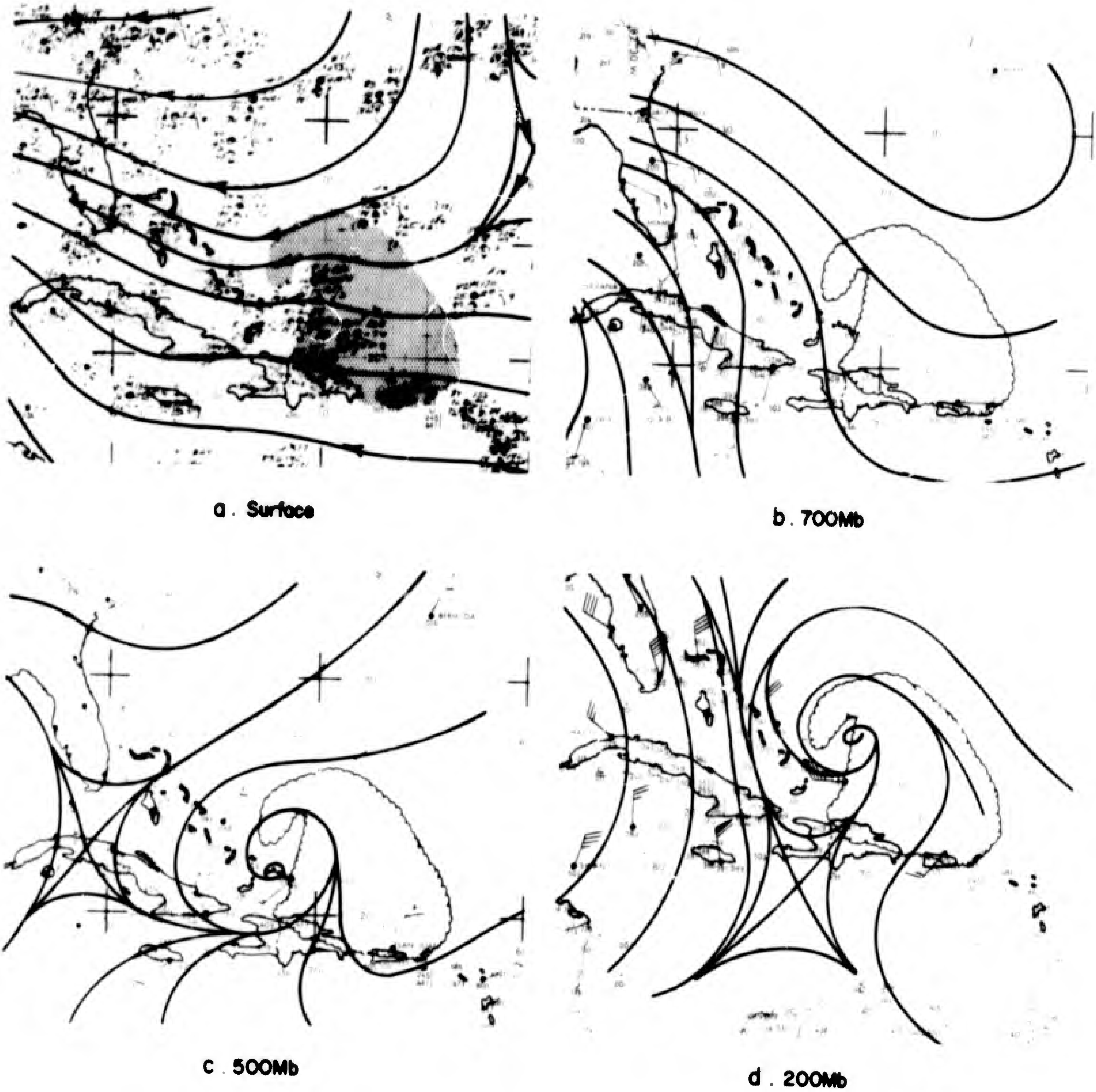


Fig. II-51 Cloud Depiction and Streamline Analyses for 1200Z, 9 September 1961 streamline analysis, however, (Fig. 11-51c) we find excellent correspondence between the two types of synoptic scale features in this area. A comparison at 200 mb shows a similar correspondence (Fig. 11-51d).

These comparisons reveal existence of a deep, upper tropospheric cyclone extending from below 500 mb to above 200 mb, while the concurrent surface flow patterns were still essentially undisturbed.

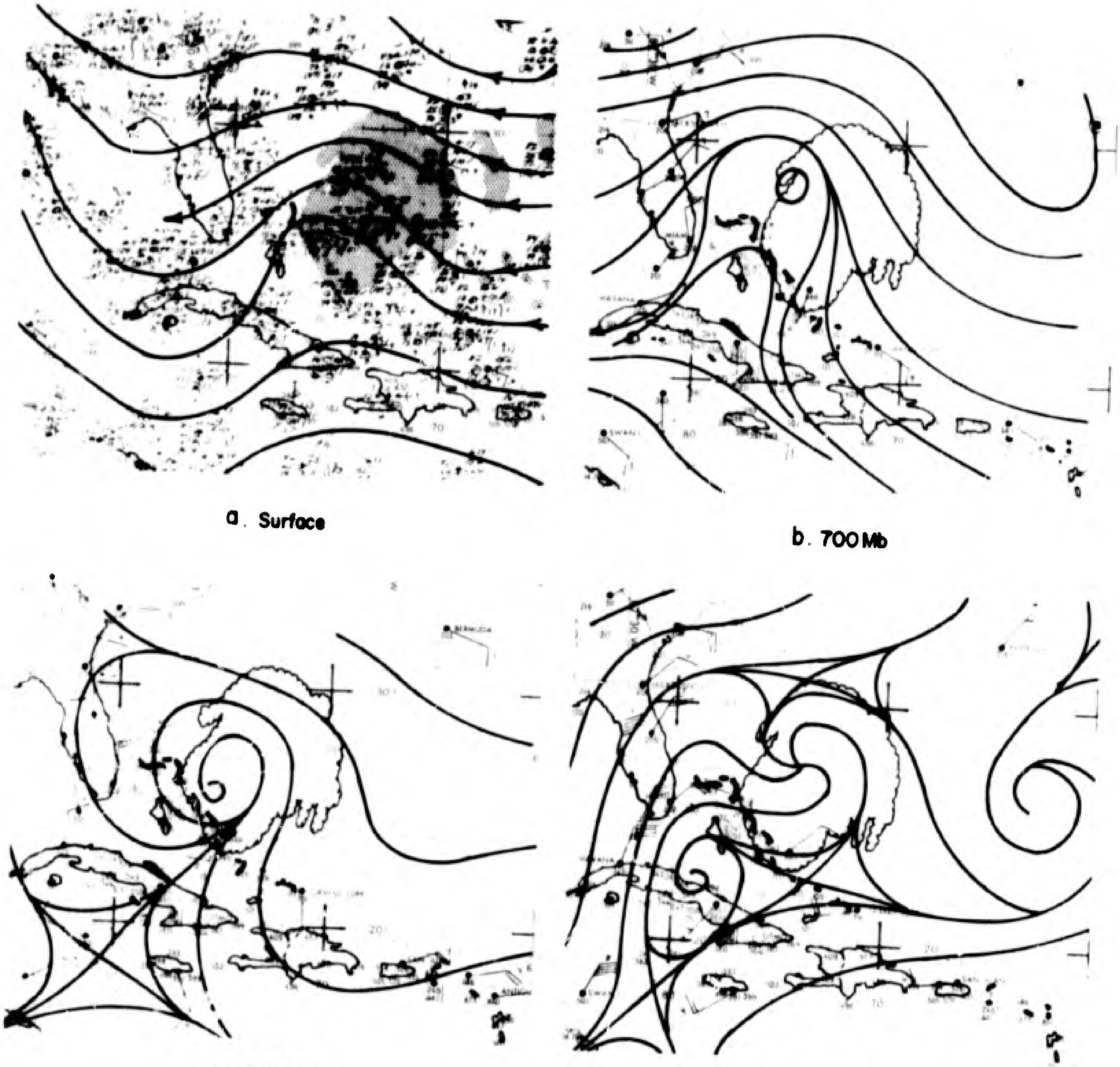
This structure persisted for the following two days (not illustrated) with little change. However, on 12 September, the surface streamlines became distorted into a distinct sinusoidal wave pattern; and a comparison with the gross pattern of cloud cover, shown in Figure 11-52a, reveals a significant increase in pattern correspondence between the low level flow and cloud cover. Comparisons at 700 mb and 500 mb (Figs. 11-52b and 11-52c) show a similar increase in pattern correspondence at 700 mb, while the correspondence at 500 mb remains as excellent as three days earlier. At higher levels, however, as shown in the 200 mb analysis in Figure 11-52d, a complete reversal had occurred and we see a weak anticyclone in place of the cyclone which had existed earlier.

At this point in the system development, some of the details often indicated by the newer nephanalysis procedures might have been very helpful. The edges of the neph vortex pattern may indicate a density gradient in the cirriform clouds which is directed away from the vortex center, as discussed in Sections 11. 5. 3 and 11. 6. 3. Unfortunately, by this point in the life of TIROS III the quality of the photographs had so deteriorated that adequate resolution was not available.

By the following day, 13 September, a well-defined cyclonic center was evident in the low level streamline analysis. A comparison with satellite-observed cloud cover, shown in Figure 11-53, indicates excellent correspondence between the streamline and cloud cover patterns which suggests a well defined cyclonic circulation extending through a fairly deep atmospheric layer. In this case, the cyclonic circulation extended from the surface to about 300 mb. The previously mentioned anticyclonic flow pattern (shown in Fig. 11-52d) still persisted at 200 mb. During the next few days this tropical depression intensified and moved northward as a small but intense tropical storm.

This interesting case has several points which seem deserving of further discussion:

a. The initial vortex cloud pattern was not related to any surface development, but was an upper level system of the type discussed in Section 11. 10. Superimposing the neph pattern successively on the streamline analyses for various levels permitted



a. Surface

b. 700 Mb

c. 500 Mb

d. 200 Mb

Fig. II-52 Cloud Depiction and Streamline Analyces for 1200Z, 12 September 1961

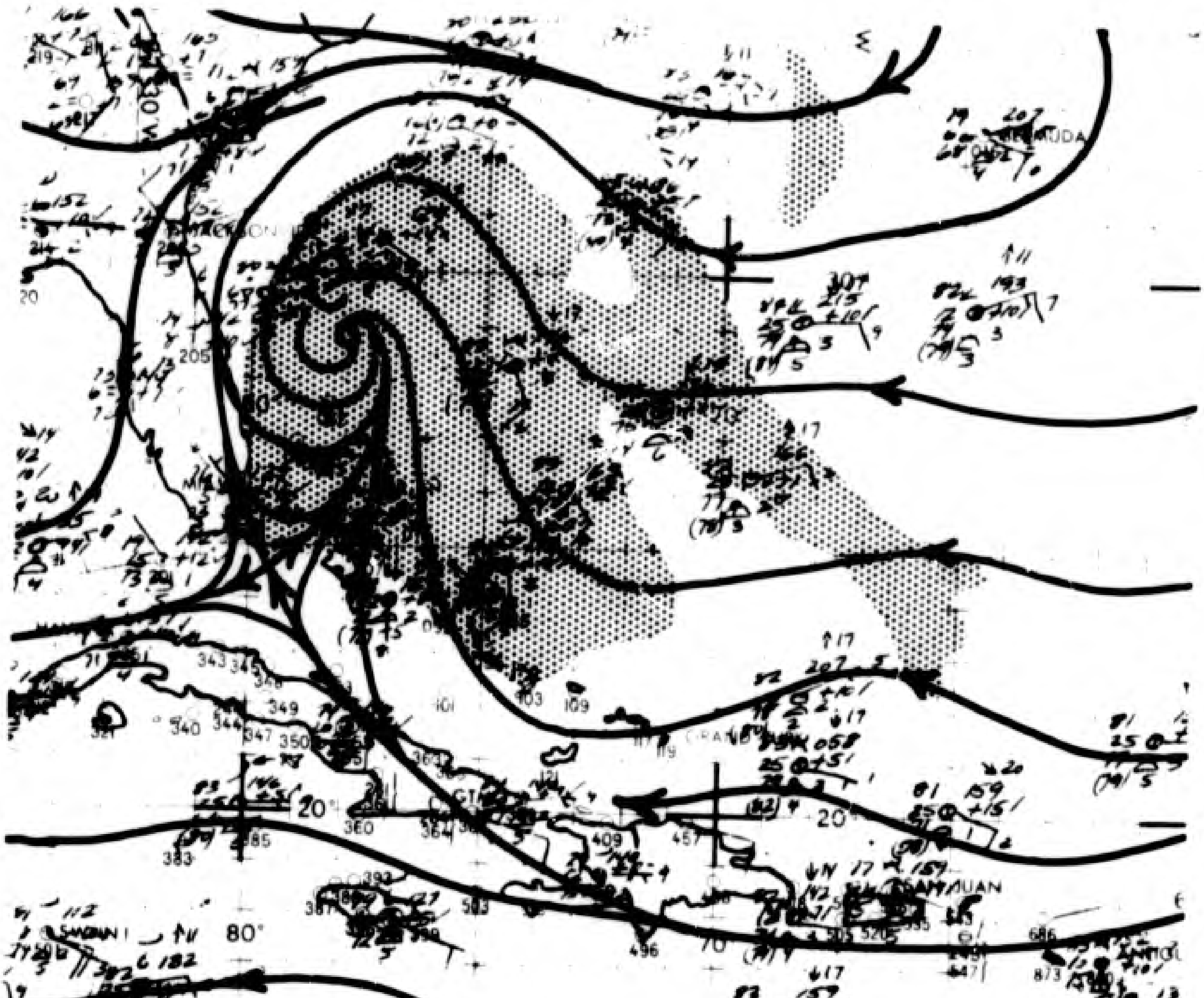


Fig. 11-53 Cloud Depiction and Surface Streamline Analysis for 1200Z, 13 September 1961

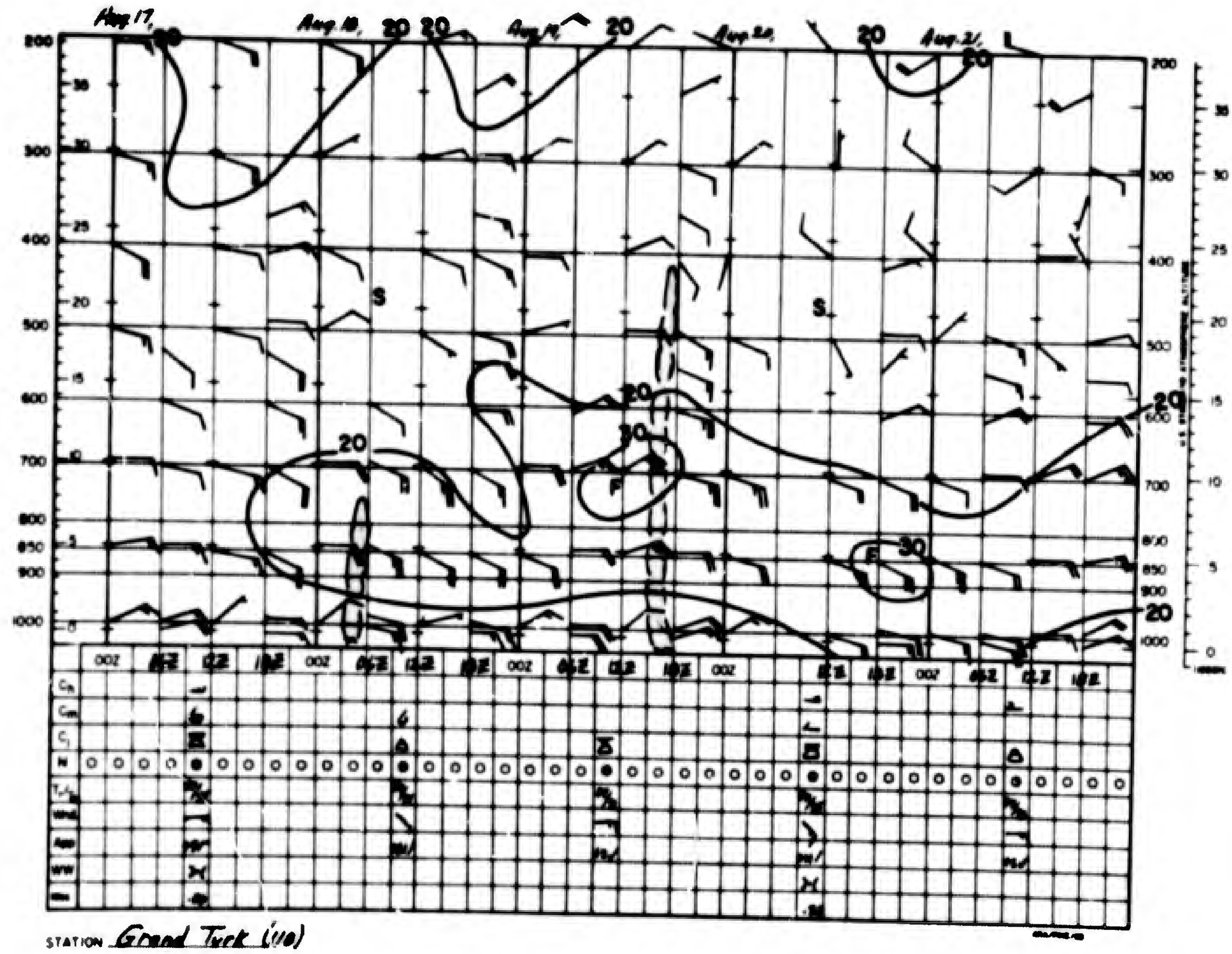


Fig. 11-54 Time Cross-section for Grand Turk Island for Period from 17-21 August 1962

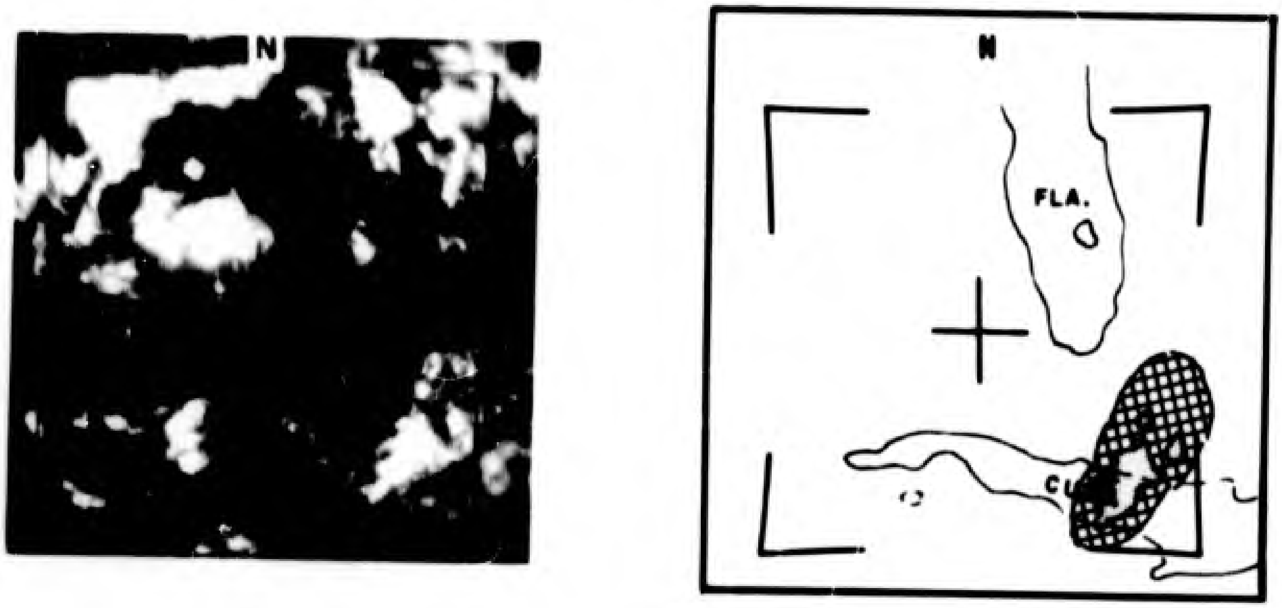


Fig. 11-55 Picture and Geographic Locator Showing a Weak Easterly Wave over Cuba. (Orbit 892D of TIROS V about 1800Z, 20 August 1962)

a determination of the layer within which the cloud vortex existed. This procedure is applicable even in areas of extremely limited upper level data coverage, since a single wind observation or the nature of the analysis in adjoining areas may provide an analysis key when evaluated with respect to satellite observations.

b. The existence of a well organized vortex pattern often indicates existence of a cylconic circulation of considerable vertical depth.

c. The existence of an apparent cloud vortex does not always indicate a cyclonic circulation at the top of the layer in which the clouds exist. An anti-cyclonic outdraft will have nearly the same appearance as a cyclonic indraft, as discussed in Section 11.5.

d. A cloud vortex which is associated with a deepening cyclone will usually exhibit more organization in the foreward (relative to direction of motion) quadrants than a non-deepening cyclone.

e. Optimum utilization of all available data is required for accurate analysis. The satellite data are not being used to their fullest when considered separately from other sources of information.

11.12.4 Time Cross-Sectio s As An Additional Aid To Tropical Satellite Analysis

The time-honored procedure of preparing time cross-sections in tropical areas, as mentioned near the beginning of this chapter, acquires a new perspective when used with satellite data. Careful consideration of the time changes of atmospheric flow and structure during related satellite observation periods can often permit inferences as to the spatial distribution and structure of atmospheric flow patterns relating to the cloud patterns. Figure 11-54 shows a time cross-section[74] at Grand Turk Island for the period 17-21 August 1962. This particular period relates to the weak easterly wave, shown in Figure 11-55, which passed over eastern Cuba about 1800Z of August 20.

The Grand Turk time cross-section shows a slight cyclonic shift in the winds at all levels about 1800Z on 19 August. Satellite data plus the time cross-section would have permitted the analyst to determine whether this wind shift was related to a larger cyclone further to the south, or to a weak easterly wave as was actually the case. In fact, the analyst without satellite data might even ignore the slight wind shift. The satellite data permit evaluation of the wind shift as a part of the overall picture, thereby insuring a more complete and accurate analysis.

CHAPTER 12

CONTRIBUTIONS OF METEOROLOGICAL SATELLITE DATA TO WEATHER FORECASTING

The primary contribution of meteorological satellite data to improved weather forecasts, at least at present, is through the achievement of a better analysis, after which appropriate conventional forecasting techniques can be applied. Depending on the circumstances, these forecasting techniques may range from the simplest of pencil-measured extrapolations to the most sophisticated numerical weather prediction models; regardless of the technique to be applied, it is obviously more likely to be successful when applied to a superior analysis.

As has been emphasized repeatedly during previous chapters of this report, this better analysis is least likely to result from use of either the satellite or the conventional data alone; it requires the integrated use of both types of data appropriately weighted as to the density of available conventional data.

12.1 ANALYSIS ASPECTS ESPECIALLY APPLICABLE TO FORECASTING

There are certain situations in which the satellite data may directly affect the forecast. When satellite data become available before or at a time intermediate to standard synoptic charts, they may indicate developments of a nature not earlier anticipated; say the suddenly intensified organization of a nascent cyclone, or an upper air trough unexpectedly closing off to form a closed low aloft. Such use of satellite data can be likened to a "Met Watch"* procedure, and in fact should be included in conduct of the Met Watch.

In some situations, satellite data may provide at least directional information with regard to winds aloft, with cloud bands (especially jet stream cirrus-see Section 7.1.3) or cirrus blowoffs and the direction of their cloud density gradients (see Sections 8.1.2.3 and 11.6.3) serving as keys. Such wind information is not only of direct operational concern but indicates the nature of existing steering currents which should be considered in predicting the future motions of weather systems in the vicinity of these currents.

* Maintaining a surveillance of weather conditions for a specific area or flight, so a warning of unforecast conditions can be given without delay.

Satellite data can often aid in the initial detection, proper identification, or improved interpretation of smaller sized disturbances such as secondary vortices (see Section 5.3, 6.2.5.1 and 11.9), short wave upper-level troughs (see Section 5.4 and 6.2.3.1), and various areas of cloud and/or precipitation which appear anomalous when considered in terms of conventional cyclone models and their idealized precipitation patterns. Once detected and identified, these features (which may often otherwise be missed) can then be appropriately considered when preparing the forecast.

As discussed in Chapter 8, the satellite data often provide information as to the existence, position, form, extent, etc., of mesoscale systems that may not otherwise be available to the forecaster. These data can be used to significantly improve shorter period forecasts, such as those of terminal and in-flight weather conditions.

Several critical Air Force missions, especially reconnaissance and in-flight refueling, specifically require cloud cover forecasts. The satellite provides a direct and vivid map of current cloud cover, whose future position can then be estimated using appropriate extrapolation and/or advection techniques modified to include expected diurnal effects and anticipated system developments.[108]

12.2 INCIPIENT CYCLOGENESIS

Satellite data may indicate incipient developments prior to evidence becoming apparent in other synoptic data. In both tropical and extratropical regions, any bending, folding, bulging, or thickening of a major cloud band should alert the analyst to possible subsequent developments, although obviously not every distorted cloud band is associated with an area of cyclogenesis (see Sections 5.5, 6.2.1, 11.1.2 and 11.3).

In the tropics, major amorphous cloud masses, sometimes referred to as cloud "blobs",[95] should also be monitored as sometimes being initial indicators of developing systems (see Section 11.1.1).

12.3 VORTEX MOTION

12.3.1 Extratropical Vortices

Useful relationships appear to exist between the orientation of the major vortex cloud band and the direction of motion of the vortex system for the following 24 hours. Successful application of these results is extremely dependent on correct estimation of the intensity of the vortex system. The steps required are listed below:[70]

a) If the vortex is in the pre-occlusion (Fig. 6-6) or early occluded (Figs. 6-7, -10, -11) stage, the vortex system will move parallel to a direction obtained by averaging the orientation of the (frontal cloud) band starting at its eastward limit and continuing westward until 10° west of the vortex center. The use, in this averaging, of segments which subtend approximately a 30° angle, measured from the vortex center, is recommended.

b) If the vortex is in the fully occluded stage, expected motion will be parallel to the general orientation of the major cloud band.

In some examples of the pre-occlusion stage, the direction of future motion is indicated by the orientation of an isolated thin bright band which is located in the cold air west of the poleward bulge of cloudiness and between the center of the bulge and frontal cloud band. This band often seems to parallel the jet stream. Figure 6-6 illustrates this band (west of the main cloud mass); note the parallelism of the band and the double arrow showing the direction of system motion.

12.3.2 Tropical Vortices

As discussed in Section 11.6.4, pre-hurricane convective bands (or squall lines) are usually observed to be in the forward quadrant of the storm, and often are oriented approximately perpendicular to the direction of motion. Furthermore, the tendency for the wider portion of an asymmetrical cloud canopy to favor the right side of the storm relative to the direction of motion (in the northern hemisphere) also provides a potential for estimating future storm motion. While neither of these indicators is foolproof, the combination of them, or one of them and other indicators and techniques based on conventional data, may provide a more reliable estimate of subsequent storm motion than any single indicator or technique alone.

12.4 TROPICAL STORM DEVELOPMENT

The intensification of tropical disturbances is often signaled by the shift of the apparent center of circulation from the east to the west side of the central cloud mass, and related other changes, as discussed in Section 11.4.3. Small bright areas near the centers of tropical storms, apparently the images of penetrative convective towers (see Section 11.5.2), and/or cirrus streamers indicating (from the gradient of cloud density) outflow from the storm at high levels (see Section 11.5.3) are also apparently indicators of storm intensification.

12.5 THE SATELLITE AND FORECASTING

The following discussion, only very slightly modified from its original wording as prepared prior to even the launch of the first Sputnik[128] (and more than three years before TIROS I), is still largely valid:

"Present-day forecasting techniques and the data to be expected from a satellite are not (entirely)* compatible. The primary factors a forecaster uses in his business are the four-dimensional fields of motion, pressure, and temperature. While it is hoped the satellite will be able to gather some data of these types through the use of radiometers, at best they will be far inferior in both quality and quantity to our present domestic observations. It is expected the primary observations made by a satellite will be of clouds, which are presently treated as secondary factors in forecasting.

"This leads to two possible avenues of attack: to tailor the satellite data to the forecaster or to tailor the forecaster to the data. The former seems the surer path. It means the primary objective is not to devise true forecasting techniques based on satellite data; instead, it involves devising means of translating satellite data into the kinds of information that are important to present-day techniques. However, this does not imply complete disregard of the alternative. As a secondary objective, consideration should be given to the possibility that this new viewpoint will lead to fundamental changes in our understanding of the atmosphere and may, therefore, lead to radically different forecasting techniques."

* The insertion of this word "entirely" is the only modification of the original wording. The justifications for this seemingly minor but actually most significant addition can be found throughout this report.

In a related vein, it has been suggested* that, as far as the forecaster is concerned, the pressure field and frontal analysis provide largely a crutch - supplying an artificial frame into which he forces the data to make them fit, a preconceived model for better or worse. (In Section 11.4, we noted the unfortunate consequences of analogous tendencies with regard to the Easterly Wave concept). Perhaps in time the forecaster may develop the ability to discard these artificial aids as a consequence of learning how to handle most effectively the real atmosphere and its weather systems as they are so graphically depicted, in their full glory, by the satellite data. There is no exaggeration to the now frequently quoted statement: "Nature uses clouds to draw its own weather map, which the satellites allow us to use."

While such developments would presumably be favorable to the improved forecasting of weather, per se, there will still remain the problem of deriving from satellite observations, with improved accuracy, the quantitative physical measurements needed for application of numerical weather prediction techniques, and to satisfy certain operational requirements such as winds for navigation, winds and densities for ballistic calculations, etc.

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* By a meteorologist with extensive past experience and daily demonstrated current proficiency in both meteorological research and practical weather forecasting.

[illegible]

CHAPTER 13

OPERATIONAL APPLICATIONS OF SATELLITE INFRARED DATA

Although at the time of preparation of this report no satellite radiation observations were being made available for operational use in weather analysis, the following discussion is included to provide guidance in the use of such data by Air Weather Service forecasters at such time as operational data are disseminated.

The satellite infrared data most likely to first become operationally available* will provide information with regard to:

1. Gross resolution patterns of cloud cover, and areas without clouds, especially at night when the TV cameras cannot provide data. The resolution and detail available from the infrared (IR) data will be less than that in the TV pictures. (See Section 13.2).

2. Approximate temperatures of the cloud tops of overcast areas, from which approximate cloud top heights can be inferred. Depending on the particular satellite sensors used for the IR observations, these data may be available either only at night, or for both day and night.

3. For clear areas, approximate temperatures of the ground or ocean surface. Again depending on the sensor used, these data may be available only at night.

13.1 A SIMPLIFIED EXPLANATION OF THE BASIS OF INFRARED OBSERVATIONS FROM SATELLITES

Since all objects and most gases with temperatures greater than absolute zero (-273°C) radiate energy at infrared wavelengths, such radiation is emitted by the earth, by clouds, and by the atmosphere. The amount of radiation emitted is related to:

1. The temperature, with greater amounts of radiation emitted at higher temperatures.

* Research now underway may make it possible, some years from now, for major weather centrals to integrate satellite cloud picture and radiometric observations. This would permit the dissemination to field forecasters of a summarized depiction of cloud amount, and approximate cloud heights and opacities.

2. The nature or emissivity of the surface, for objects such as the earth and clouds. For the earth and most clouds of reasonable thickness, except cirrus, the variation of the emissivity* from unity is small and can be neglected for many operational meteorological purposes.

3. The amount of those atmospheric constituents which absorb and emit infrared radiation. The atmospheric gases of concern can be limited to carbon dioxide (essentially a constant amount in the atmosphere), water vapor (whose variation in amount and distribution is significant), and, to a lesser extent, ozone. Dust in the atmosphere may also be a factor in satellite infrared measurements.

Bodies such as the earth and clouds radiate over all parts of the infrared spectrum, with the wavelength of peak radiation depending on temperature. Typical wavelengths of peak radiation are:

20°C	(293°K)	9.8 microns
0°C	(273°K)	10.5 microns
-50°C	(223°K)	12.8 microns
-73°C	(200°K)	14.4 microns

Gases radiate (and absorb) strongly in specific wavelength bands, and weakly or not at all in others.

It is possible to calculate the proportion of the total infrared energy radiated, over a small part of the spectrum, by a body or a known amount of gas at a given temperature. Thus, from a measurement of the energy sensed in a limited but known part of the spectrum, the surface temperature of the observed body or the temperature of the gas can be deduced.

Assume a region in the infrared spectrum where atmospheric absorption and emission are insignificant, and that the earth and atmosphere are observed from a satellite using a sensor which responds only to radiation within this region. Because the ground surface is normally at a higher temperature than are the tops of clouds, areas observed to have warm temperatures (say between -10°C and +20°C) could usually be assumed to be clear, while those with colder temperatures (such as below -20°C) might be assumed to be cloud covered except in polar regions or other areas where very low surface temperatures are to be expected. And, because temperature usually decreases with height, the colder the temperature the higher the cloud tops.

* The emissivity of a surface is the ratio of the energy actually emitted to that emitted by a perfect radiator (or "black body") at the same temperature.

If radiosonde data were available for the area (or even climatological values of average lapse rates), the approximate height of cloud tops could be deduced from the cloud top temperature.

This is, in the simplest form, the way infrared observations can be used to observe cloud-covered areas at night. From some satellites, infrared data usable in daytime are also available. Cold areas are deduced to be cloudy; warm areas clear. Areas of abrupt temperature gradients (in the infrared) are assumed to indicate the boundaries between clear and cloudy areas.

In practice, there are of course complications:

13.1.1 Effects of Atmospheric Gases

In almost all parts of the infrared spectrum there is at least slight absorption and emission by certain atmospheric gases. The greater the amount of variable gas (water vapor is the one of prime concern), the greater its absorption. Let us now assume a clear area with surface temperature of 0°C, and with a humid atmosphere over it. Some of the IR energy leaving the surface would be absorbed by the water vapor which, because of the normal decrease of temperature with height, would be colder and so would emit IR energy at a lower rate than would the surface. Since the moist atmosphere would emit less energy than it absorbed, the net radiation reaching the satellite sensor would be somewhat reduced compared to that originally emitted from the earth's surface. Because of this, a 0°C ground surface might appear to the satellite to have a temperature of, say, -5°C.

This apparent decrease in temperature, as observed from the satellite in the infrared, is of less consequence for dry air. It is also less for high clouds, as compared to low clouds or the surface, because of the relatively small amounts of water vapor (or most other gases) in the upper atmosphere. The decrease is also usually less with cold temperatures, because cold air can hold less moisture.

Because the path length through the atmosphere is greater when the sensor looks at an angle as compared to vertically down, the observed decrease in apparent temperature becomes greater as the angle of view moves further from the vertical.

Dust in the atmosphere, including possible thin layers well into the stratosphere, may also reduce the apparent temperature of the earth's surface or of a cloud top as measured by a satellite infrared sensor.

13.1.2 Effects of Scattered or Broken Clouds

The instantaneous field of view of most meteorological satellite IR sensors covers an area ranging from a few miles to a few tens of miles across. Accordingly, with scattered to broken clouds, some of the field of view may include clouds while the rest is clear. In such cases, the energy reaching the sensor comes in part from the warmer earth and in part from the colder clouds; the resulting radiometer reading is thus a value between that for clear skies and that for an overcast at the level of the partial cloud cover. Thus, a partial cloud cover with tops at, say, 15,000 feet might appear the same to the radiometer as an overcast with tops at, say, 8,000 feet. The difference can be resolved only from other types of data, or from synoptic climatological considerations. Here again, the integration of satellite and available conventional data is desirable to obtain the best possible synoptic analysis.

13.1.3 Thin Clouds and Cirrus

In the case of thin clouds, and apparently also for most cirrus, part of the infrared energy reaching the satellite sensor is radiation that originated at the earth's surface, or from a lower cloud deck, and was able to penetrate the clouds without being completely absorbed. Since the lower levels are normally warmer and so produce more energy, the net effect is a radiometric value representative of cloud tops at a lower height than they actually are; i.e., the same effect as that of a partial cloud cover. In one case observed by TIROS[39,131], with cirrostratus over a heavy lower cloud cover, pilot-observed cloud heights were reported as slightly above 30,000 feet while the satellite radiometer readings suggested cloud tops near 25,000 feet.

13.1.4 Identification of Low Clouds

The lower the cloud tops, the less the difference in temperature between cloud covered and clear areas. With low clouds and a stable, isothermal atmosphere in the lower levels, there would be no difference; with a low level inversion (such as is common over arctic areas in winter) and clouds extending to about the top of the inversion, the cloud tops would be warmer than the surface.

The radiometers flown to date have an uncertainty in their temperature readings of about ± 3°C.[105] Furthermore, the effects of water vapor on the apparently observed temperatures are usually greatest in the lower (and most humid) layers of the atmosphere. Accordingly, from infrared observations it is difficult or impossible to reliably detect clouds with tops below about 5,000 feet.

13.1.5 Sensor Degradation

The IR sensors flown so far appear to degrade, in accuracy and sensitivity, after relatively short times in orbit.[105,121,122] While this degradation particularly effects absolute energy values, and so the ability to deduce temperatures and cloud heights, it is of less concern as regards the temperature differences and gradients used to distinguish between clear and cloud-covered areas.

13.2 SPECIFIC RADIATION MEASUREMENTS

At this writing, it is impossible to be precise as to the instruments from which the first operationally available satellite infrared data will come, or the form of presentation to the forecaster. The most likely sources are described below, with discussions of those characteristics of primary concern to the potential operational user.

13.2.1 Channel 2 of the TIROS Scanning Radiometer

The TIROS Channel 2 measurements are made in the spectral region from about 8-13 microns, which is often referred to as a "window" because at those wavelengths atmospheric absorption and re-emission are relatively low. The examples of operational applicability of infrared data presented later in this section use TIROS Channel 2 data, since they were the only applicable data readily available, even for research use, at this writing. Details as to the radiometer, beyond those necessary for practical use of the data and presented below, have been published in several places.[4,79,105]

This radiometer integrates (or averages) the energy from a field of view that varies from a circle about 30 nautical miles in diameter when looking vertically below the satellite, to approximately an ellipse of 60 x 100 nautical miles when the viewed areas lie about 600 nautical miles from the satellite subpoint.[40] At greater distances from the subpoint, the minimum resolved area is even greater. Thus, for most practical purposes, the best resolution of the radiometer data varies from about 30 to over 100 nautical miles; and, accordingly, a single data point corresponds to about the same or a greater area than the entire area normally visible (from horizon to horizon) to a ground observer making a cloud observation. This of course limits the degree of detail visible in the cloud patterns when observed in the IR.

The 8-13 micron window is not perfectly transparent, but rather is "dirtied" by atmospheric absorption. This absorption results principally from water vapor, and to a lesser extent from carbon dioxide and ozone. As discussed in Section 13.1.1, the effect of these partial absorptions is to reduce the apparent temperature observed by the radiometer. Although these reductions vary with the amount of water vapor and the angle of view, average values can be assumed as approximately:[118,119]

Satellite Observed Temperature		Approximate Correction (to be added to observed temperature)
290°K	(+17°C)	10°C
280°K	(+ 7°C)	7°C
260°K	(-13°C)	4°C
240°K	(-33°C)	2°C
220°K	(-53°C)	0°C

13.2.2 The Nimbus High Resolution Infrared Radiometer

The Nimbus High Resolution Infrared Radiometer (HRIR) operates in another atmospheric window centered at about 3.7 microns.[7,47] The field of view varies from a circle about 5 nautical miles in diameter when looking directly below the satellite, to approximately an ellipse of 7 x 14 nautical miles when the viewed area lies about 600 nautical miles from the subpoint. At greater distances from the subpoint, the resolved area is, of course, even greater. Again, these factors limit the resolution of the radiometer data to between 5 and over 20 miles. The probable errors in the apparent temperatures as measured by this radiometer are estimated to be about ± 4°C.

Because the HRIR radiometer operates in the near infrared region of the spectrum where there is still significant reflected solar radiation as well as emitted infrared radiation, quantitatively useful HRIR data are not expected to be available during daylight portions of each orbit.

While the effects of partial atmospheric absorption on the apparent temperatures as observed by the HRIR are not yet known precisely, they are expected to be less than those for the TIROS Channel 2 data. Since the effects of carbon dioxide are probably predominant and that gas varies only slightly in concentration, the effects are also expected to be less variable. (See also note added in proof, at end of this Chapter).

13.2.3 The Nimbus Medium Resolution Infrared Radiometer, Channel 2

Channel 2 of the Nimbus Medium Resolution Infrared Radiometer (MRIR) operates in the 10-11 micron portion of the atmospheric window. Because this portion of the window is particularly transparent, effects of atmospheric absorbers, particularly water vapor, are expected to be much less than for the TIROS Channel 2 data. Channel 2 measurements of radiometers flown on TIROS subsequent to TIROS VIII may also use this narrower and so better portion of the window.

Otherwise, from the viewpoint of the operational user, the characteristics of the MRIR Channel 2 data[106, 107] are essentially the same as those of Channel 2 of the TIROS Scanning Radiometer. (Note: MRIR was not flown on Nimbus I).

13.3 INTERPRETATION AND USE OF WINDOW IR DATA

Because they can provide information on cloud cover and cloud height at night over large areas, infrared data for atmospheric windows are potentially another extremely useful tool for synoptic analysis. Studies to date regarding potential synoptic uses of the TIROS infrared data have generally used the Channel 2 atmospheric window data,[39, 114, 120, 121, 122] and the examples to be presented here will be taken from such studies. The types of synoptic applications so demonstrated would be equally applicable to use of both TIROS and MRIR Channel 2 data both day and night, and to HRIR data obtained at night; accordingly, operational use of the infrared atmospheric window data awaits only availability of that data to Air Weather Service stations.

Since the format and therefore the effective detail (or resolution) of the data to be made available to the operational forecaster is still unknown (except, of course, that it cannot be better than the limiting sensor resolutions as described in Section 13.2), the resolutions of the data as presented in the examples below have no specific significance. Cases are used here only because they are readily available from existing studies. In Section 13.3.1, the data analyzed were averaged TIROS Channel 2 observations for $5^{\circ} \times 5^{\circ}$ latitude-longitude squares. They demonstrate that considerable synoptic information can be derived even with data of such poor resolution. Section 13.3.2 illustrates the far greater information made available when the data are used in approximately their fullest fidelity; it seems likely that the data would be operationally disseminated with resolutions more nearly equivalent to those used in this case.

The cases in Sections 13.3.1 and 13.3.2 will illustrate both existing techniques for analysis of the infrared data and some of the interpretations which are possible over areas of dense and sparse conventional data.

13.3.1 Synoptic Scale Features Depicted by TIROS Channel 2 IR Data

TIROS Channel 2 data averaged over $5^{\circ} \times 5^{\circ}$ latitude-longitude squares reveal synoptic scale patterns.[120,121,122] Figures 13-1 and 13-2 show examples of such analyses. The IR data were taken on several adjacent orbits between approximately 0800 and 1630Z, and can be related to the 1200Z surface maps.

For the northern hemisphere south of 60°N, in July, areas with radiation temperatures colder than 260°K (-13°C)* are considered as broken or overcast areas with cloud tops probably higher than 10,000 feet. Since this analysis averages over rather large areas, it is almost certain that some cloud tops in these areas extended well above 10,000 feet. In areas where the radiation temperatures were below 240°K (-33°C), cloud tops higher than 25,000 would certainly be expected.

Conversely, extratropical areas where the average temperatures are greater than 280° (equal to an actual value of about 287°K if the corrections outlined in paragraph 13.2.1 are considered) are either areas of clear skies, or at most scattered to broken clouds with tops no higher than 8,000 - 10,000 feet.

* In Figures 13-1 and 13-2, the hundreds digit is omitted from the radiation temperature isolines since the observed values were all within the range 201° to 299°K.

Fig. 13-1 Surface Analysis 1200Z, 15 July 1961, and Channel 2 T_E Pattern, Orbits 42-47, TIROS III. The T_E Units are in ^{o}K with the 200 Prefix Omitted (i.e. 70 = $270^{o}K$)

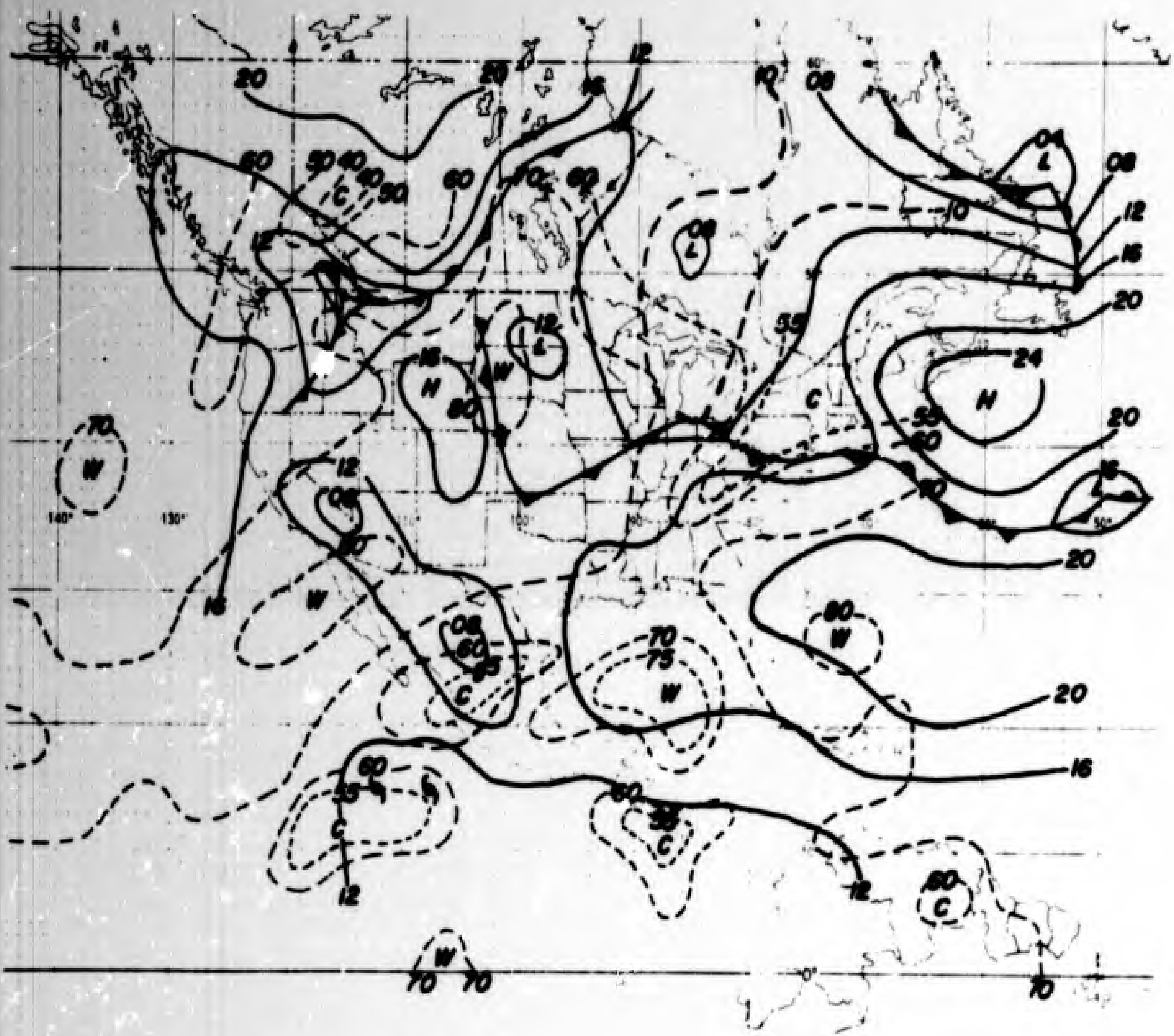

Fig. 13-2 Surface Analysis 1200Z, 16 July 1961, and Channel 2 T_E Pattern, Orbits 56-63.

Although many significant areas are apparent in Figures 13-1 and 13-2, only four synoptic features, over or near the Continental U. S., will be discussed here. These cases illustrate that synoptic scale patterns and areas of significant weather can be mapped with the Channel 2 IR data even at the gross scale used here.

13. 3. 1. 1 Open Wave Pattern

An area of cold temperatures is apparent, in Figure 13-1, over the northeastern U. S. and southeastern Canada. The surface analysis shows an open wave over the Great Lakes. The 500 mb center was centered nearly over Duluth, with a small amplitude wave east of the center. Relatively warm radiation temperature values ($T_r \geqslant 270$) exist in the warm sector of the open wave, with colder values of T_r (below 260°K) to the north, east, and west of the open wave center. The warm sector T_r values are probably indicative of broken low cloudiness, as confirmed by the concurrent TIROS nephanalysis (Fig.13-3). The wave form of the overcast north of the surface center can also be clearly seen. During the following 24 hour period, nearly one inch of rain was reported by stations in the region enclosed by the 260°K isotherm. The center of the area (colder than 230°K) was probably associated with the area of positive vertical motion related to the 500 mb short wave trough.

13. 3. 1. 2 Bermuda High Pattern

The area of mostly clear skies associated with the Bermuda high is well marked by the 280°K isotherm on Figure 13-1. Good correlation exists (in this particular case) between the area over and near the Gulf of Mexico enclosed by the 280°K isotherm and the 1020 mb surface isobar. On the following day (Fig. 13-2) the area enclosed by the 280°K isotherm again correlates reasonably well with the 1020 mb isobar and marks the eastward regression of the Bermuda high. Continued movement eastward of the area enclosed by the 280°K isotherm on 17 July (not shown) marked the further regression of the Bermuda high and an increased probability of less favorable weather conditions in the Gulf of Mexico.

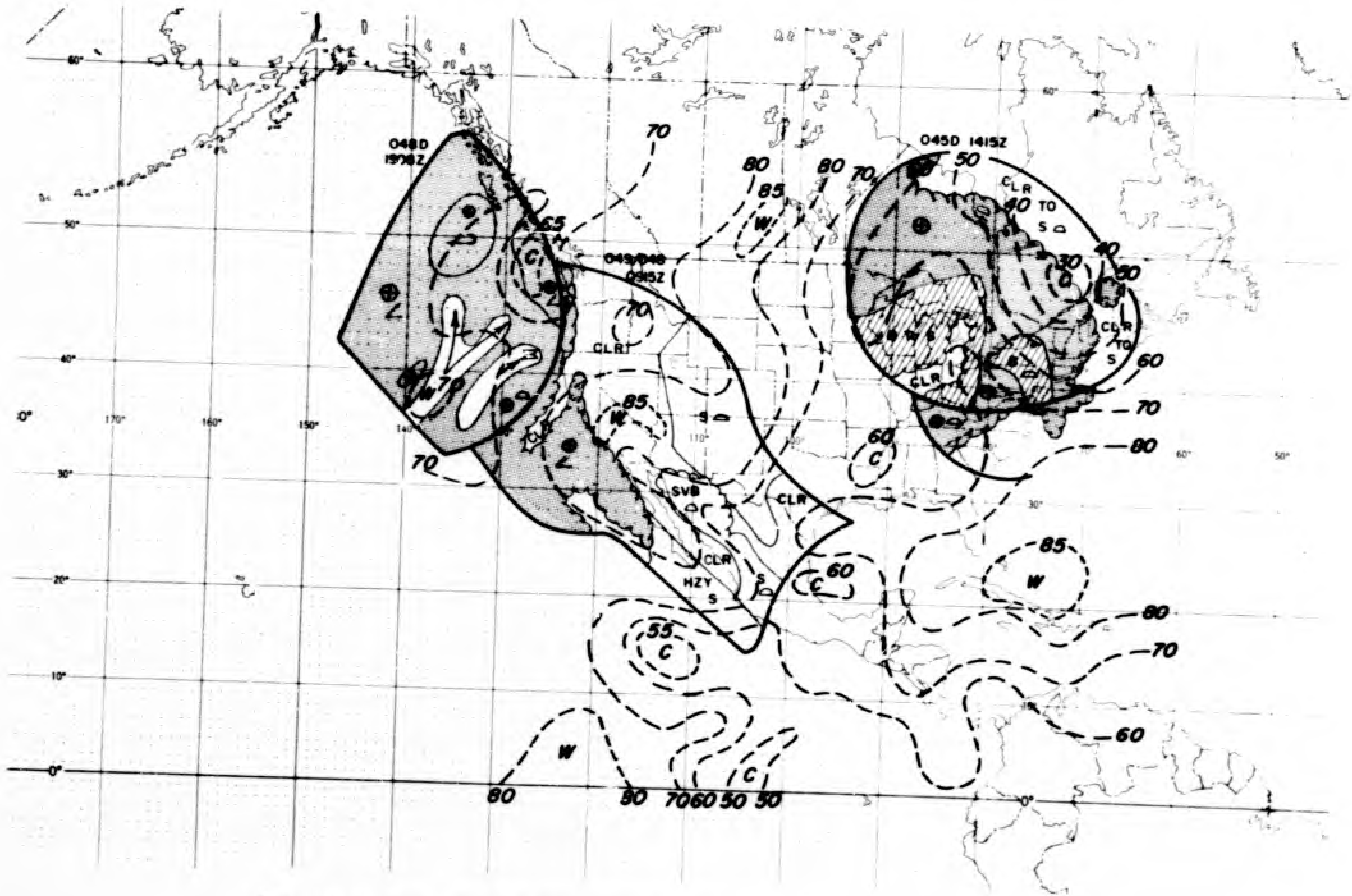

Fig. 13-3 Nephanalysis and Channel 2 Pattern, Orbits 42-47. TIROS III

13.3.1.3 Squall Line Pattern

Figure 13-2 shows a tongue of cold radiation temperatures extending along the western edge of the Applachian Mountains and suggests conditions not indicated by the frontal analysis. Frontal analyses over continents in mid July are often misleading. Skies along the front, which lies generally east-west along 40°N, are generally clear or scattered west of the Mississippi. The only significant weather east of the Rockies is occurring within the area enclosed by the 260°K isoline where cumulus congestus clouds are reported, and in two small areas of cumulonimbus activity over northern Florida. The geometry of the cold temperature tongue suggests a developing squall line, which is supported by conventional reports of convective development and by the TV pictures. Figure 13-4 is a mosaic of TIROS III pictures (taken at about 1645Z, somewhat later than the IR data of Fig.13-2) of the southern part of the area enclosed by the 260°K isoline. As shown in Figure 13-4, the cloud line at 1645Z extends across western Tennessee to northern Mississippi.

Cloud tops with temperatures colder than 255°K are indicated by the radiation data. The actual height of the 255°K isotherm was at about 22,000 feet. Since the highest cloud tops undoubtedly cover only a small portion of the 5° squares, it is probable that some of these clouds extended above 30,000 feet.

By 1800Z thunderstorms had begun over western Tennessee and northeastward along the center line of the tongue of cold temperatures. This squall line moved slowly eastward and the similar map for 17 July (not shown) indicated its presence by a trough of cold temperatures just off the east coast of the United States. Precipitation amounts in excess of 0.6 inches were associated with many portions of the line.

The example clearly shows a case where immediate practical use can be made of 8-12 micron atmospheric window data when they are available in real time. Again radiometer data should not be considered as standing by themselves, but should primarily be another observation available to the forecaster for integration with the total applicable data.

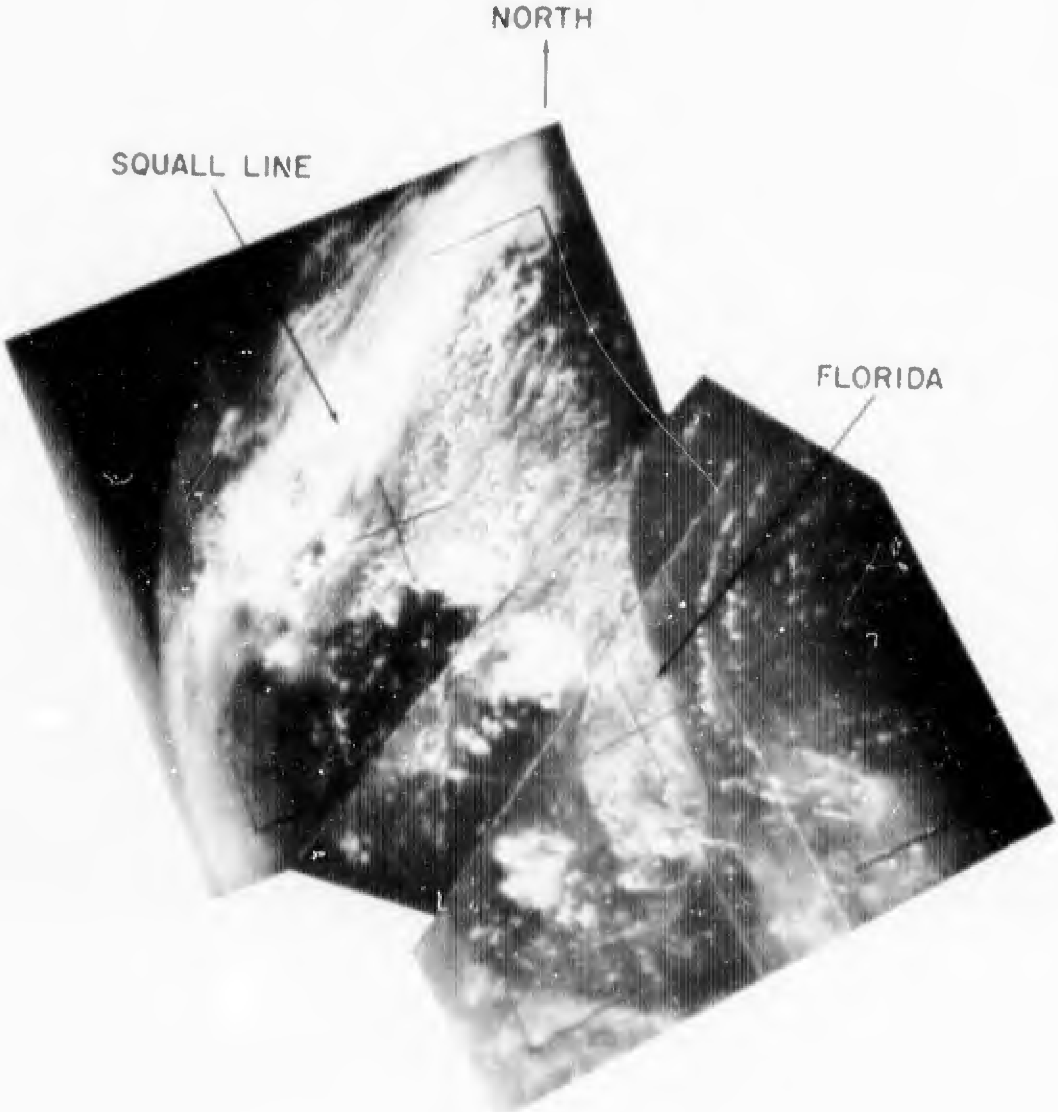

FIG. 13 - 4 Mosaic from orbit 62, 16 July 1961 showing squall line, isolated thunderstorm complexes over northern Florida, and thin cumulus lines east of Florida.

13.3.1.4 Hurricane Watch

An area of very cold T_r can be seen (in both Figs. 13-1 and 13-2) in the vicinity of $15^{\circ}N$, $110^{\circ}W$. On 15 July, the Weather Bureau placed hurricane Kathleen about 2° northeast of the coldest area (T_r less than $255^{\circ}K$). A pronounced bulge in the $260^{\circ}K$ isotherm can be noticed near the coast of Mexico. On 16 July (Fig. 13-2), a second hurricane (Liza) was identified; both hurricanes are shown in Figure 13-2. At this time also, a very cold area is noted along the Pacific coast of Nicaragua and Costa Rica. By 17 July (not shown), this area had moved slightly westward and contained T_r values lower than $240^{\circ}K$. By 20 July, a hurricane named Madeline was located about $14^{\circ}N$, $117^{\circ}W$, and almost surely developed from the disturbance noted on the IR data. Cases such as this indicate the radiometric data can be extremely useful in discovering probable nascent hurricanes, which can then be more fully examined by reconnaissance aircraft or other available techniques.

13.3.2 A Higher Resolution Analysis

An example of a higher resolution study[39,91] of an orbital pass over the United States is presented in Figure 13-5. These data, obtained on November 23, 1960, are again for the 8 to 12 micron window region. The temperatures are expressed in terms of $^{\circ}K$. The isotherm interval is $10^{\circ}K$; the dot-dash lines are intermediate $5^{\circ}K$ isotherms. A feature of interest is the frontal zone near the east coast of the United States, where very low values of radiation were obtained (Fig. 13-5). This front was nearly stationary with wave developments along it. The lowest radiation temperature values tend to be mainly southeast of the front. Note the sharp gradient of temperature to the north and west of the front. Generally, there are high temperatures from the Appalachian Mountains to the central part of the United States. Temperature gradients throughout this region are relatively small. Further west over the Great Plains and Rocky Mountains more complicated patterns are found.

Figure 13-6 is a cloud chart based on conventional data only. (TIROS II pictures, although available for this time, were rather poor). This chart was based not only on surface data but also on radiosondes and pilot reports. It includes an analysis of the heights of cloud tops in the broken and overcast areas. Only three contour lines have been drawn: 30,000, 10,000, and 5,000 feet. It is interesting that the very lowest radiation values were in the area where the tops of the upper

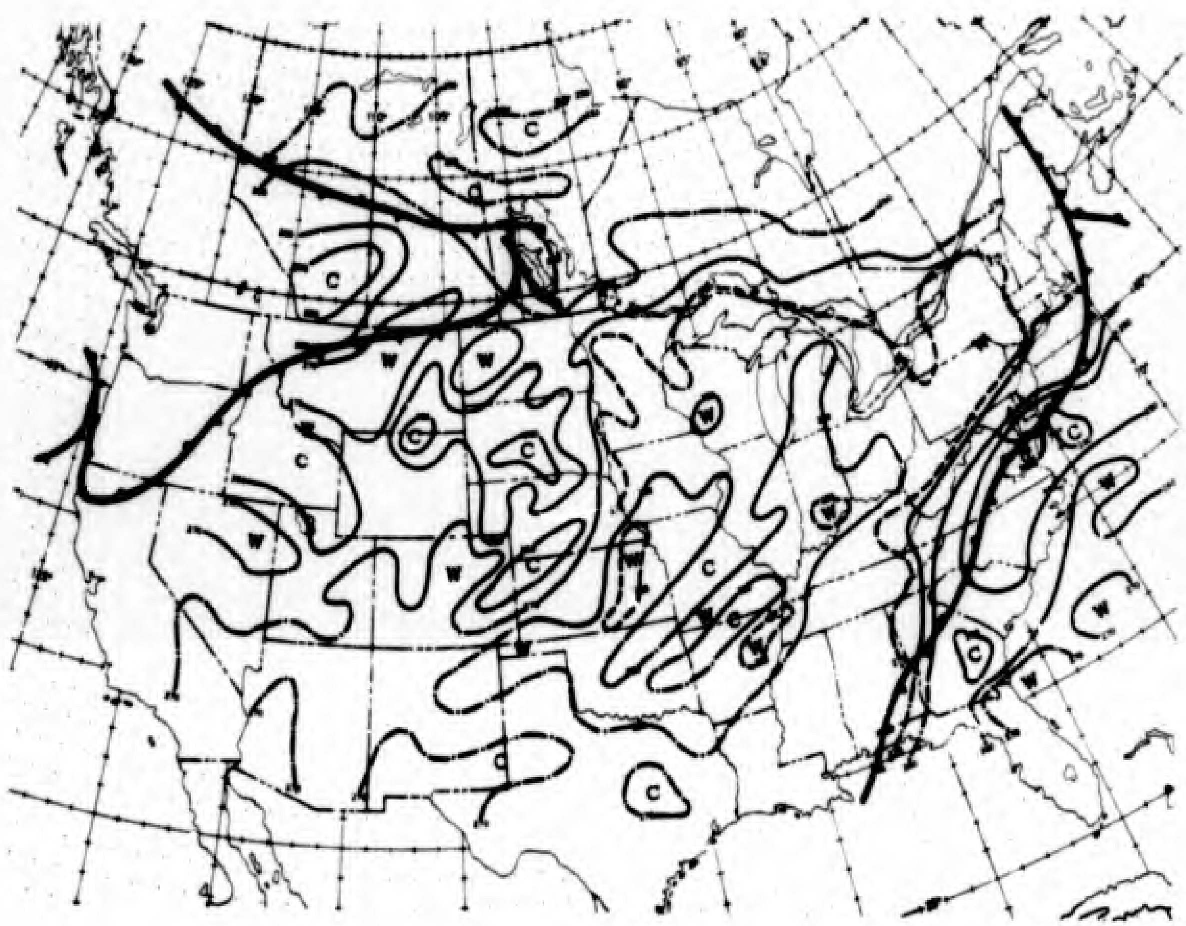

Fig. 13-5 TIROS II Radiation Data, 8 to 12 Micron Window, 1810Z, 23 November 1960. Temperature in °K (From Reference 39).

Fig. 13-6 Cloud Cover Chart for 1800Z, 23 November 1960. Solid Lines are Contours of Height of Cloud Tops in Thousand's of Feet (From Reference 131)

cloud layer of an extensive multilayered cloud system were more than 30,000 feet. Pilots reported heights of 33,000 feet or more in this area. Furthermore, the area of rainfall nearly coincided with the zone of the highest cloud tops and lowest radiation temperatures (i.e., less than about 250°K).

Note the very abrupt change in cloud height over the region near 39° north and 75° to 80° west from the high cirrostratus above 30,000 feet to a layer of altostratus-altocumulus with tops at about 15,000 feet and then to broken and scattered stratocumulus clouds at about a hundred miles to the northwest. The radiation gradient (Fig. 13-5) was extremely strong in this region, showing a very sharp change from low to high values over Pennsylvania, where the clouds become scattered stratocumulus and then the skies clear toward the northwest. In the Midwest satellite-measured temperatures were within about 1° to 5°K of the surface air temperatures. The area over the Great Plains was covered by cirrus and cirrostratus clouds which apparently were rather thin. Underneath this cirrus and cirrostratus was an altostratus cloud layer with tops estimated to be about 18,000 feet. This is the area where two cold centers are shown in Figure 13-5. These roughly coincide with the shape of the altostratus cloud area underneath the cirrostratus (Fig. 13-6).

Figure 13-7 shows estimates of the heights of the tops of clouds derived from the satellite temperature values of Figure 13-5 with the aid of the vertical temperature distribution. (The temperature distribution of the standard atmosphere could possibly be used, but on the average a better estimate can be made over most of the Northern Hemisphere by use of isotherm charts prepared daily in the National Meteorological Center for several constant pressure surfaces. In many areas these may be crude estimates, but in other areas they are rather good.) Note that over the eastern United States heights of 27,500 feet or more were obtained. Between this region and Pennsylvania there is a sharp drop in heights to 5,000 feet or less, which generally agrees with Figure 13-6. Southwestward along the frontal zone the heights continue relatively high, but then there is a very sharp decrease to 5,000 to 10,000 feet over Georgia and Alabama. This region is still overcast, as may be seen in Figure 13-6, but the overcast consists of stratocumulus clouds with tops around 5,000 to 10,000 feet which agree well with the estimates made from the radiation data. In the area of scattered clouds or clear skies, the height values shown in Figure 13-7 essentially do not have much meaning. They generally give rather low values, which are close to the surface of the earth. Over the Dakotas the maximum values are 17,500 feet. In other words, the satellite seems to be "looking"

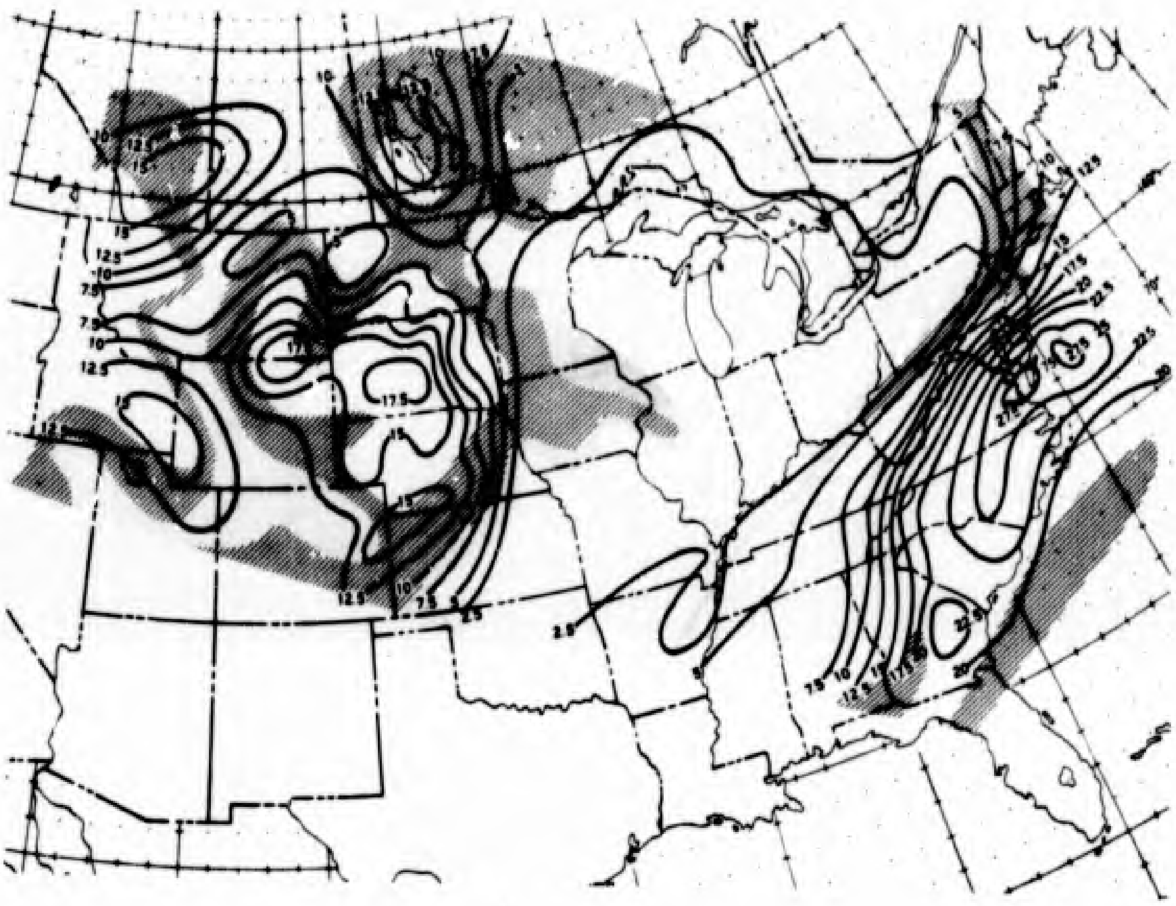

Fig. 13-7 Height of Cloud Tops (Thousands of Feet), 1800Z, 23 November 1960, as Estimated from TIROS II Radiation Measurements. Hatched Areas are the Broken Clouds of Figure 13-6; Dotted Areas are the Scattered Clouds of Figure 13-6 (From Reference 131).

through the cirriform clouds (shown in Fig. 13-6) to the tops of the altostratus. The cirrus and cirrostratus are apparently rather thin and are not absorbing and em' .ing much radiation in the window region.

Returning to the area of high clouds near the east coast, the height estimates from the satellite measurements are only about 22,000 to 28,000 feet, whereas heights of 30,000 to 33,000 feet were estimated from the pilot reports and other data. Since the cirrostratus clouds were rather thick, about 7,000 feet, the heights derived from the satellite temperature values correspond to the lower parts of the cirrostratus (or slightly below their bases). Thus, the cirrostratus clouds were only partially transparent to infrared radiation and were not making a substantial contribution to the infrared radiation measured by the satellite.

In summary, this case definitely illustrates that the radiation data in the 8-12 micron water-vapor window can be very useful for approximate cloud top determinations both night and day. In the daytime these data would be most useful in conjunction with satellite pictures. At night these data would be the only information on cloudiness available and would at least be useful for detecting extensive middle and high cloud systems.

Several other examples of relatively high resolution synoptic analyses using TIROS Channel 2 radiation data can be found in Reference 89.

13.4 VALUE OF THE IR DATA

The value of these data, integrated with available conventional and satellite cloud picture data, would seem to be self-evident. Analyses for large sparse data areas can be enchanced, and indeed analyses may be drawn where they are not now possible.* When these data become operationally available and nighttime cloud cover analyses can be drawn from them, it may be possible to deduce cloud pattern movements on a 12 hour basis. Because of the obvious value of IR cloud cover data, especially when integrated with picture and conventional data, it is to be hoped that IR data, perhaps in the form of radiation temperature maps, will become available as an operational tool in the reasonably near future.

* Initial results of studies presently in progress at ARACON Geophysics Company indicate that at least the gross outlines of vortex cloud patterns associated with extratropical cyclonic storms can be identified in the TIROS Channel 2 Infrared data.

NOTE ADDED IN PROOF:

The first samples of the Nimbus I HRIR data have provided vivid views of the earth and its cloud cover, with a degree of detail closely approaching that of the better TIROS TV pictures. Lakes, rivers, and coastlines are clearly seen, indicating a distinct ability to discriminate between objects in the field of view with only small differences in temperature. Cloud patterns are easily seen.

The data require some care in interpretation, because when displayed as a photo-facsimile produced picture they superficially but closely resemble the views seen in TIROS pictures; it requires a distinct effort to remember that the visible contrasts are those in temperature and not in reflectivity. Nevertheless, it is obvious that HRIR data should be of great value to operational as well as research meteorology.

A small portion of one HRIR strip (Fig. 13-8, p. 310) showed Hurricane Dora over northern Florida, and the middle Atlantic coast of the United States. The data are reproduced with cold areas (clouds) white, and warm areas dark. The temperature sensitivity of HRIR is demonstrated here by the clearly visible coast, the warm ocean water temperatures (black) contrasting with the cooler nighttime land (grey). The excellent resolution is shown by Dora's eye, and the distinct shapes of Chesapeake and Delaware Bays.

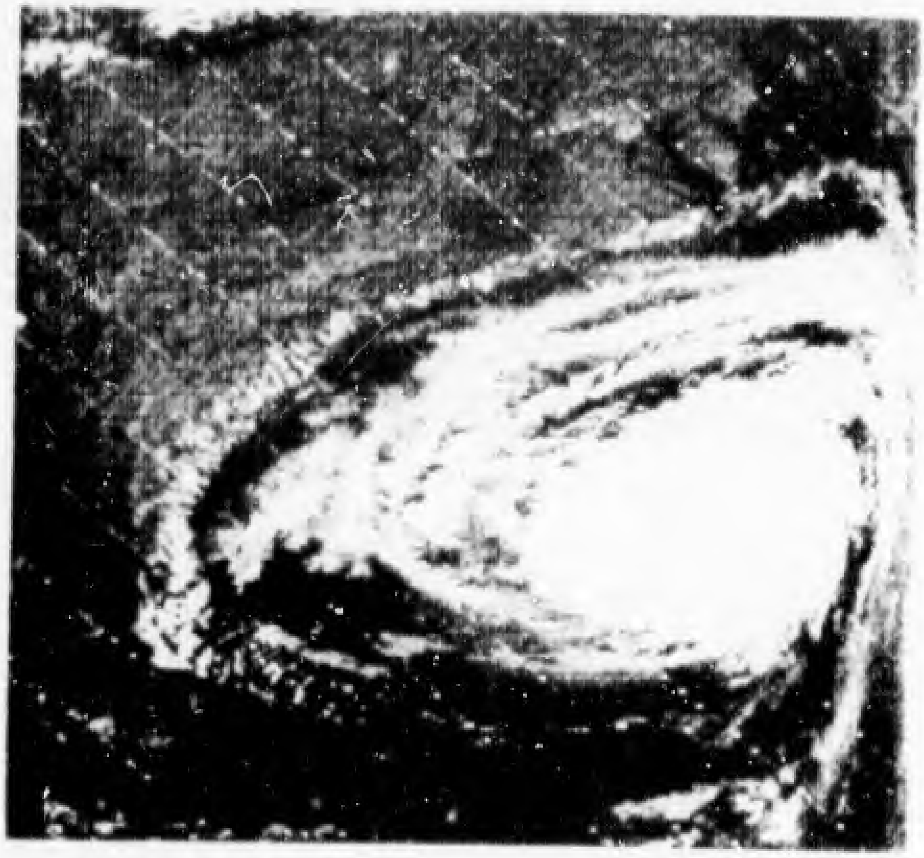

Fig. 13-8 Hurricane Dora, and the Middle Atlantic Coast of the United States, as Seen by the Nimbus I HRIR

REFERENCES

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REFERENCES

1. Albert, E. G., and R. W. White, 1962: Analysis of TIROS Picture Rectification Errors, National Weather Satellite Center, USWB.

2. Baliles, M. D., and H. Neiss (Ed)., 1963: Conference on Satellite Ice Studies, Meteorological Satellite Laboratory Report No. 20, NWSC, USWB.

3. Bandeen, W. R., 1961: Earth Oblateness and Relative Sun Motion Considerations in the Determination of an Ideal Orbit for the Nimbus Meteorological Satellite, NASA Technical Note D-1045.

4. Bandeen, W. R., et al, 1961: "Infrared and Reflected Solar Radiation Measurements from the TIROS II Meteorological Satellite," Journal of Geophysical Research, 66 (10), pp. 3169-3185.

5. Bates, C. C., 1958: "Current Status of Sea Ice Reconnaissance and Forecasting for the American Arctic," Polar Atmosphere Symposium, Part I, Meteorology Section, Pergamon Press, London and New York, pp. 285-322.

6. Bergeron, T., 1951: "General Survey in the Field of Cloud Physics," International Union of Geodesy and Geophysics, Assoc. Meteor., Ninth General Assembly Memoirs, Brussels, pp. 120-134.

7. Blankenship, J. R., 1962: "An Approach to Objective Nephanalysis from an Earth-Oriented Satellite," Journal of Applied Meteorology, 1 (4), pp. 581-582.

8. Boucher, R. J., C. J. Bowley, E. S. Merritt, C.W.C. Rogers, P. E. Sherr, and W. K. Widger, Jr., 1963: Synoptic Interpretations of Cloud Vortex Patterns as Observed by Meteorological Satellites, Final Report, Contract No. Cwb 10630, ARACON Geophysics Company.

9. Boucher, R. J., and R. J. Newcomb, 1962: "Synoptic Interpretation of Some TIROS Vortex Patterns: A Preliminary Cyclone Model," Journal of Applied Meteorology, 1 (2), pp. 127-136.

10. Bowley, C. J., A. H. Glaser, R. J. Newcomb, and R. Wexler, 1962: "Satellite Observations of Wake Formation Beneath an Inversion," Journal of Atmospheric Sciences, 19 (1), pp. 52-55.

11. Bristor, C. L. and M. A. Ruzecki, 1960: "TIROS I Photographs of the Midwest Storm of April 1, 1960," Monthly Weather Review, 88 (9/12), pp. 315-326.

12. Brodrick, H. J., Jr., 1964: TIROS Cloud Pattern Morphology of Some Mid-Latitude Weather Systems, Meteorological Satellite Laboratory Report No. 24, National Weather Satellite Center, U. S. Weather Bureau.

13. Conover, J. H., 1959: Cloud Patterns and Related Air Motions Derived by Photography, Final Report, Contract No. AF 19(604)-1589, Blue Hill Meteorological Observatory, Harvard University.

14. Conover, J. H., 1962: Cloud Interpretation from Satellite Altitudes, Air Force Cambridge Research Laboratories Research Note 81.

15. Conover, J. H., 1963: Supplement 1 to Cloud Interpretation from Satellite Altitudes, Supplement 1 to Air Force Cambridge Research Laboratories Research Note 81.

16. Conover, J. H., 1963: "Interpretation of Clouds and Mesoscale Cloud Patterns as Seen from Satellite Altitudes," Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, pp. 388-392.

17. Conover, J. H., 1964: "Lee Wave Clouds Photographed from an Aircraft and a Satellite," Weather, 19 (3), pp. 79-85, 92.

18. Conover, J. H., 1964: "The Identification and Significance of Orographically Induced Clouds Observed by TIROS Satellites," Journal of Applied Meteorology, 3 (3), pp. 226-234.

19. Conover, J. H., and J. C. Sadler, 1960: "Cloud Patterns as Seen from Altitudes of 250-850 Miles - Preliminary Results," Bulletin of the American Meteorological Society, 41 (6), pp. 291-297.

20. Corby, G. A., 1957: " A Preliminary Study of Atmospheric Waves Using Radiosonde Data," Quarterly Journal of the Royal Meteorological Society, 83 pp. 49-60.

21. Cramer, W. P., 1963: An Investigation of Time Changes in Clouds Observed over the Gulf of Mexico and Caribbean Sea During the Period 18-23 July 1961, Masters Thesis, A & M College of Texas, May 1963.

22. Cronin, J. F., 1963: Terrestrial Features of the United States as Viewed by TIROS, Scientific Report No. 2, Contract No. AF 19(628)-2471, ARACON Geophysics Company.

23. Deardorff, J. W., 1963: "Satellite Cloud Photos and Large-scale Vertical Motion," J. Applied Meteorology, 2 (1), pp. 173-175.

24. Doos, B. R., 1962: "A Theoretical Analysis of Lee Wave Clouds Observed by TIROS I," Tellus, 14 (3), pp. 301-309.

25. Dunn, G. E., and B. I. Miller, 1960: Atlantic Hurricanes, Louisiana State University Press, Baton Rouge, (see pp. 89-90).

26. Dunn, G. E., and Staff, 1963: "The Hurricane Season of 1962," Monthly Weather Review, 91 (4), pp. 199-207.

27. Elliott, R. D., and E. L. Hovind, 1964: " On Convection Bands within Pacific Coast Storms and Their Relation to Storm Structure," Journal of Applied Meteorology, 3 (2), pp. 143-154.

28. Erickson, C. O., 1961: "Interpretation of Cloud Types," Proceedings of the International Meteorological Satellite Workshop, NASA-USWB, U.S. Government Printing Office, pp. 67-74.

29. Erickson, C. O., and L. F. Hubert, 1961: Identification of Cloudforms from TIROS I Pictures, Meteorological Satellite Laboratory Report No. 7, U. S. Weather Bureau.

30. Fawbush, E. F., R. C. Miller, and F. G. Starrett, 1951: "An Empirical Method of Forecasting Tornado Development," Bulletin of the American Meteorological Society, 32 (1), pp. 1-9.

31. Fett, R. W., 1963: "TIROS V Views Final Stages in the Life of Typhoon Sarah, August 1962:" Monthly Weather Review, 91 (8), pp. 367-373.

32. Fett, R. W., 1964: "Aspects of Hurricane Structure: New Model Considerations Suggested by TIROS and Project Mercury Observations," Monthly Weather Review, 92 (2), pp. 43-60.

33. Frank, N. L., 1963: "Synoptic Case Study of Tropical Cyclogenesis Utilizing TIROS Data," Monthly Weather Review, 91 (8), pp. 355-366.

34. Frank, N. L., 1963: "What Satellite Data Cannot Tell Us about Tropical Cyclones," Mariners Weather Log, 7 (4), pp. 113-116.

35. Fritz, S., 1961: "Satellite Cloud Pictures of a Cyclone over the Atlantic Ocean," Quarterly Journal of the Royal Meteorological Society, 87 (373), pp. 314-321.

36. Fritz, S., 1962: "Miscellaneous TIROS Pictures," Final Report on the TIROS I Meteorological Satellite System, NASA Technical Report R-131, pp. 325-334.

37. Fritz, S., 1962: "Satellite Pictures and the Origin of Hurricane Anna," Monthly Weather Review, 90 (12), pp. 507-513.

38. Fritz, S., 1963: "Snow Surveys from Satellite Pictures," Rocket and Satellite Meteorology, North-Holland Publishing Co., Amsterdam, pp. 419-421.

39. Fritz, S., and J. S. Winston, 1962: "Synoptic Use of Radiation Measurements from Satellite TIROS II," Monthly Weather Review, 90 (1), pp. 1-9.

40. Fujita, T., 1963: Outline of a Theory and Examples for Precise Analysis of Satellite Radiation Data, Research Paper No. 15, Mesometeorology Project, The University of Chicago.

41. Fujita, T., and T. Ushijima, W. S. Hass, and G. T. Dellert, Jr., 1963: "Meteorological Interpretation of Convective Nephsystems Appearing in TIROS Cloud Photographs," Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, pp. 357-387.

42. Glaser, A. H., 1957: Meteorological Utilization of Images of the Earth's Surface Transmitted from a Satellite Vehicle, Final Report under Contract No. AF 19(604)-1589, Phase II, Blue Hill Observatory, Harvard University.

43. Glaser, A. H., 1960: "A Digital System for Rapidly Processing Meteorological Satellite TV Data for Strategic Operational Use," Forecast Procedures, Final Report under Contract No. AF 19(604)-3881, Allied Research Associates, Inc., pp. 2-17.

44. Glaser, A. H., 1960: TIROS I: An Operational Evaluation of a New Meteorological Tool, Second Semi-Annual Summary Report, Contract No. AF19(604)-5581, Allied Research Associates, Inc.

45. Glaser, A. H., 1961: TIROS Meteorology, Final Report under Contract No. AF 19(604)-5581, Allied Research Associates, Inc.

46. Goldshlak, L., 1963: APT User's Guide, Scientific Report No. 1, Contract No. AF 19(628)-2471, Allied Research Associates, Inc.

47. Goldshlak, L., and R. B. Smith, 1964: Nimbus Backup Gridding: AVCS and HRIR, Technical Report No. 1, Contract No. NAS 5-3253, ARACON Geophysics Company.

48. Grenard, H. E., 1963: ARACON Gridding Program for the CDC 160-A Computer Configuration, Technical Report No. 2, Contract No. NAS 5-1204, ARACON Geophysics Company.

49. Hadfield, R. G., E. J. Wiegman, W. Viezee, and S. M. Serebreny, 1964: Meteorological Interpretation of Satellite Cloud Photographs, Final Report, Contract No. Cwb 10481, Stanford Research Institute.

50. Hanson, D. M., 1963: The Use of Meteorological Satellite Data in Analysis and Forecasting, Technical Note No. 13, Office of Forecast Development, USWB.

51. Haurwitz, B., 1949: "Internal Waves in the Atmosphere and Convective Patterns," Annals of the New York Academy of Sciences, 48, pp. 722-748.

52. Henry, W. K., and A. H. Thompson, 1963: The Texas Dew Point Front as Seen by TIROS I, Scientific Report No. 3, Contract No. AF 19(604)-8450, The A & M College of Texas.

53. Huang, T. S., E. S. Merritt, and A. H. Glaser, 1962: Meteorological Satellite System Analyses, Final Report, Contract No. AF 19 (604)-5582, Allied Research Associates, Inc.

54. Hubert, L. F., 1961: "A Subtropical Convergence Line of the South Pacific: A Case Study Using Meteorological Satellite Data." Journal of Geophysical Research, 66 (3), pp. 797-812.

55. Hubert, L. F., 1963: "Middle Latitudes of the Northern Hemisphere - TIROS Data as an Analysis Aid," Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, pp. 312-316.

56. Hubert, L., and A. F. Krueger, 1962: "Satellite Pictures of Mesoscale Eddies," Monthly Weather Review, 90 (12), pp. 457-463.

57. Hubert, L. F., and A. Timchalk, 1964: "Accuracy of TIROS Hurricane Location," Journal of Applied Meteorology, 3 (2) pp. 203-205.

58. Johnson, D. H., 1961: "The Current USWB Meteorological Satellite Program," Proceedings of the International Meteorological Satellite Workshop, NASA-USWB, U. S. Government Printing Office, pp. 25-30.

59. Jones, J. B., 1961: "A Western Atlantic Vortex Seen by TIROS I," Monthly Weather Review, 89 (10), pp. 383-390.

60. Jordan, E. S., 1953: "An Observational Study of the Upper Wind Circulation Around Tropical Storms," Journal of Meteorology, 9 (5), pp. 340-346.

61. Kreitzberg, C. W., 1964: The Structure of Occlusions as Determined from Serial Ascents and Vertically-Directed Radar, AFCRL Research Report 64-26, Air Force Cambridge Research Laboratories.

62. Krueger, A. F., and S. Fritz, 1961: "Cellular Cloud Patterns Revealed by TIROS I," Tellus, 12 (1), pp. 1-7.

63. Lautzenhiser, R. E., 1953: "Great Lakes Weather," Weatherwise, 6 (1), pp. 3-6.

64. Leese, J. A., 1962: The Role of Advection in the Formation of Vortex Cloud Patterns, GRD Research Note No. 78, AFCRL.

65. Lester, P. F., S. J. Hall, and A. H. Thompson, 1964: An Investigation of Time Variations in a Subtropical Jet Stream and the Associated Cloud Patterns as Shown by TIROS I, Scientific Report No. 7, Contract No. AF 19(604)-8450, Texas A & M University.

66. Ligda, M.G.H., 1955: "Hurricane Squall Lines," Bulletin of the American Meteorological Society, 36 (7), pp. 340-342.

67. Madvig, R. M., 1963: Phase II, Nimbus Data-Handling System, Final Report Contract No. NAS 5-1882, Stanford Research Institute (See Appendix E, Information Content of Satellite Cloud Photographs).

68. Malkus, J. S., 1963: " Cloud Patterns over Tropical Oceans," Science, 141 (3583), pp. 767-778.

69. Merritt, E. S., 1963: An Analysis of Stratiform Cloud Patterns in the Canary Islands Region, Scientific Report No. 2, Contract No. AF 19(628)-320, ARACON Geophysics Company.

70. Merritt, E. S., 1963: Fleet Applications, Meteorological Operational Satellites (Antarctic Area), Final Report, Contract No. N189(188)-56507A, ARACON Geophysics Company.

71. Merritt, E. S., 1963: Fleet Applications, Meteorological Operational Satellites (Tropics-Easterly Waves), Final Report, Contract No. N 189(188)-56897A, ARACON Geophysics Company.

72. Merritt, E. S., 1963: Personal communication.

73. Merritt, E. S., 1963: Unpublished African Area Studies; reported in Annual Summary Report under Contract No. AF 19(628)-2471, ARACON Geophysics Company.

74. Merritt, E. S., 1964: "Easterly Waves and Perturbations, A Reappraisal," Journal of Applied Meteorology, 3 (4), pp. 367-382.

75. Merritt, E. S., 1964: "Tropical Cyclone Development; A Satellite-Derived Interpretation Model," To be published in the Journal of Applied Meteorology.

76. Miller, F. R., 1963: "An Application of TIROS Cloud Observations in Sparse Data Regions," Monthly Weather Review, 91 (9), pp. 433-451.

77. Nagle, R. E., 1962: Comparison of Time Integrated Radar Detected Precipitation with Satellite Observed Cloud Patterns, Scientific Report No. 1, Contract No. AF 19(628)-284, Stanford Research Institute.

78. Nagle, R. E., and S. M. Serebreny, 1962: "Radar Precipitation Echo and Satellite Cloud Observations of a Maritime Cyclone," Journal of Applied Meteorology, 1 (3), pp. 279-295.

79. Nordberg, W., 1961: "Physical Measurements and Data Processing," Proceedings of the International Meteorological Satellite Workshop, NASA-USWB, U. S. Government Printing Office, pp. 107-120.

80. Oliver, V. J., 1962: "Comparison of a Satellite Nephanalysis with a Conventional Weather Analysis for a Family of Pacific Frontal Storms," Final Report on the TIROS I Meteorological Satellite System, Technical Report R-131, NASA, pp. 273-279.

81. Oliver, V. J., 1963: Personal communication.

82. Oliver, V. J., et al, 1964: Personal communication.

83. Palmén, E., 1951: "The Aerology of Extratropical Disturbances," Compendium of Meteorology, American Meteorological Society, Boston, pp. 599-620.

84. Palmer, C., C. W. Wise, L. J. Stempson, and G. H. Duncan, 1955: The Practical Aspects of Tropical Meteorology, Air Weather Service Manual 105-48.

85. Petterssen, S., 1956: Weather Analysis and Forecasting, Vol. I, Motion and Motion Systems, 2nd. ed., Mc Graw-Hill Book Company, Inc., New York, 428 pp.

86. Petterssen, S., 1956: Weather Analysis and Forecasting, Vol. II, Weather and Weather Systems, 2nd ed., McGraw-Hill Book Co., Inc., New York, 266 pp.

87. Petterssen, S., 1960: "Some Weather Influences due to Warming of the Air by the Great Lakes in Winter," Proceedings of the Third Conference on Great Lakes Research, Ann Arbor, Michigan.

88. Randerson, D., and A. H. Thompson, 1964: Investigation of a TIROS III Photograph of the Florida Peninsula Taken on 14 July 1961, Scientific Report No. 6, Contract No. AF 19(604)-8450, Texas A & M University.

89. Rao, P. K., and J. S. Winston, 1963: "An Investigation of Some Synoptic Capabilities of Atmospheric 'Window' Measurements from Satellite TIROS II," Journal of Applied Meteorology, 2 (1), pp. 12-23.

90. Riehl, H., 1945: Waves in the Easterlies and the Polar Front in the Tropics, Misc. Rpt. No. 17, University of Chicago.

91. Riehl, H., 1954: Tropical Meteorology, McGraw Hill Book Company, New York.

92. Rutherford, G. T., 1962: "Satellite Cloud Photographs - Their Application in Synoptic Analysis," WMO Bulletin, 11 (4), pp. 188-194.

93. Ruzecki, M. A., 1963: The Use of Satellite Cloud Photographs in Numerical Weather Prediction, Meteorological Satellite Laboratory Report No. 23, National Weather Satellite Center, U. S. Weather Bureau.

94. Sadler, J. C., 1963: "Utilization of Meteorological Satellite Cloud Data in Tropical Meteorology," Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, pp. 333-356. (Also published as AFCRL Research Note, August 1962).

95. Sadler, J. C., 1963: "Satellite Meteorology Program at the University of Hawaii," Final Report of the 3rd U. S.-Asian Weather Symposium, 1st Weather Wing, Air Weather Service.

96. Sadler, J. C., 1963: TIROS Observations of the Summer Circulation and Weather Patterns of the Eastern North Pacific, Scientific Report No. 5, Contract No. AF 19(604)-6156, Hawaii Institute of Geophysics.

97. Sadler, J. C., 1963: Tropical Cyclones of the Eastern North Pacific as Revealed by TIROS Observations, Scientific Report No. 4, Meteorology Division, Hawaii Institute of Geophysics, University of Hawaii.

98. Sanders, F., 1963: Further Research Directed Toward the Study of Relations of Atmospheric Flow to Weather, Final Report, Contract No. AF19(604)-8373, Department of Meteorology, Massachusetts Institute of Technology.

99. Sawyer, J. S., 1950: "An Example of Cyclogenesis in Relation to Sutcliffe's Theory of Development," Centenary Proceedings, Royal Meteorological Society, pp. 107-113.

100. Schuetz, J., and S. Fritz, 1961: "Cloud Streets over the Caribbean Sea," Monthly Weather Review, 89 (10), pp. 375-382.

101. Scorer, R. S., 1949: "Theory of Waves in the Lee of Mountains," Quarterly Journal of the Royal Meteorological Society, 75, pp. 41-56.

102. Serebreny, S. M., E. J. Wiegman, and R. G. Hadfield, 1962: Investigation of the Operational Use of Cloud Photographs from Weather Satellites in the North Pacific, Final Report, Contract No. Cwb-10238, Stanford Research Institute.

103. Serebreny, S. M., and E. J. Wiegman, 1964: The Distribution of Clear Air Turbulence Reports and Cloud Patterns as Seen in Satellite Photographs, Final Report, Contract No. Cwb-10481, Stanford Research Institute.

104. Singer, S. F., and R. W. Popham, 1963: "Non-meteorological Observations from Weather Satellites," Astronautics and Aerospace Engineering, 1 (3), pp. 89-92.

105. Staff Members, 1962: TIROS III Radiation Data Users' Manual, Aeronomy and Meteorology Division, Goddard Space Flight Center, NASA.

106. Stampfl, R., 1963: The Nimbus Spacecraft and Its Communication System as of September 1961, NASA Technical Note D-1422.

107. Stampfl, R., and H. Press, 1962: "Nimbus Spacecraft System," Aerospace Engineering, 21 (7), pp. 16-28.

108. Stone, R. G., 1957: A Compendium on Cirrus and Cirrus Forecasting, Air Weather Service Technical Report 105-130.

109. Stuart, D. W., 1961: Vertical Motion and the Baroclinic Mechanism of Rapid Upper Level Cyclogenesis, Scientific Report under NSF Grant No. 18048, Department of Meteorology, University of California at Los Angeles.

110. Sutcliffe, R. C., 1953: "Cyclone and Anticyclone; a Comparative Study," Proceedings of the Toronto Meteorological Conference, Royal Meteorological Society, pp. 139-143.

111. Timchalk, A., and L. F. Hubert, 1961: "Satellite Pictures and Meteorological Analyses of a Developing Low in the Central United States," Monthly Weather Review, 89 (11), pp. 429-445.

112. van der Ham, C. J., 1962: "TIROS Pictures of the European Area," Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, pp. 317-322.

113. Van Dijk, M. H., and G. T. Rutherford, 1963: "A TIROS III Interpretation Exercise Over Southeast Australia," Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, pp. 305-311.

114. Viezee, W., and P. A. Davis, 1964: Analysis and Interpretation of Daytime Radiation Data, Scientific Report No. 2, Contract No. AF19(628)-2777, Stanford Research Institute.

115. Vines, B., 1898: Cyclonic Circulation and Translatory Movement of West Indian Hurricanes, U. S. Weather Bureau, Washington, D. C.

116. Wark, D. Q., and R. W. Popham, 1962: Ice Photography from the Meteorological Satellites TIROS I and II, Meteorological Satellite Laboratory Report No. 8, USWB.

117. Wark, D. Q., R. W. Popham, W. A. Dotson, and K. S. Colow, 1962: "Ice Observations by the TIROS II Satellite and by Aircraft," Arctic, 15 (1), pp. 9-26.

118. Wark, D. Q., G. Yamamoto, and J. H. Lienesch, 1962: "Methods of Estimating Infrared Flux and Surface Temperature from Meteorological Satellites," Journal of the Atmospheric Sciences, 19 (5), pp. 369-384.

119. Wexler, R., 1962: Interpretation of TIROS II Radiation Measurements, Final Report, Contract No. AF 19(604)-5968, Allied Research Associates, Inc.

120. Wexler, R., 1963: Synoptic Interpretations and Heat Balance Determination from TIROS II Radiation Data, Scientific Report No. 1, Contract No. AF 19(628)-429, ARACON Geophysics Company.

121. Wexler, R., 1964: "Infrared and Visual Radiation Measurements from TIROS III," Applied Optics, 3 (2), pp. 215-219.

122. Wexler, R., and P. Sherr, 1964: Synoptic Analysis of TIROS III Radiation Measurements, Final Report, Contract No. AF 19(628)-429, ARACON Geophysics Company.

123. Whitney, L. F., Jr., 1961: "Another View from TIROS I of a Severe Weather Situation, May 16, 1960," Monthly Weather Review, 89 (11), pp. 447-460.

124. Whitney, L. F., Jr., 1963: "Severe Storm Clouds as Seen from TIROS," Journal of Applied Meteorology, 2 (4), pp. 501-507.

125. Whitney, L. F., Jr., and S. Fritz, 1961: "Tornado Producing Cloud Pattern Seen from TIROS I," Bulletin of the American Meteorological Society, 42 (9), pp. 603-614.

126. Widger, W. K., Jr., 1961: "Satellite Meteorology - Fancy and Fact," Weather, 16 (2), pp. 47-55.

127. Widger, W. K., Jr., 1964: "A Synthesis of Interpretations of Extratropical Vortex Patterns as Seen by TIROS," Monthly Weather Review, 92 (6), pp. 263-282.

128. Widger, W. K., Jr., and C. N. Touart, 1957: "Utilization of Satellite Observations in Weather Analysis and Forecasting," Bulletin of the American Meteorological Society, 38 (9), pp. 521-533.

129. Widger, W. K., Jr., and C. P. Wood, 1961: "An Explanation of the Limitations to the Coverage Provided by TIROS," Weatherwise, 14 (6), pp. 230-237.

130. Winston, J. S., 1960: "Satellite Pictures of a Cut-off Cyclone Over the Eastern Pacific," Monthly Weather Review, 88 (9/12), pp. 295-314.

131. Winston, J. S., 1961: "Applications of Radiation Data to Synoptic Analysis and to Studies of the General Circulation," Proceedings of the International Meteorological Satellite Workshop, NASA-USWB, U. S. Government Printing Office, pp. 129-137.

132. Winston, J. S., 1961: "Use of TIROS Pictures in Current Synoptic Analysis," Proceedings of the International Meteorological Satellite Workshop, NASA-USWB, U. S. Government Printing Office, pp. 95-106.

133. Winston, J. S., and L. Tourville, 1961: "Cloud Structure of an Occluded Cyclone over the Gulf of Alaska as Viewed by TIROS I," Bulletin of the American Meteorological Society, 42 (3), pp. 151-165.

COMMUNICATION
PRACTICES

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APPENDIX A

COMMUNICATION PRACTICES

This appendix provides information as to current communication practices with regard to circuits, codes, and schedules used for the dissemination of:

1. Alert messages providing data on anticipated areas of satellite coverage.
2. Satellite cloud pictures and nephanalyses.

A. 1 ALERT MESSAGES WITH REGARD TO PROGRAMMED AND PREDICTED SATELLITE COVERAGE

1. Circuits and Facilities
   a. International Service O TTY Circuits: 8276, 205T, 233, 235
   b. Domestic Fax Circuits: National Fax, High Altitude, JQEJA 796 (the old 1R9 Strategic Fax net)
   c. Overseas Radio Fax:

(1) Transmission out of New York and beamed toward Europe on a mean azimuth bearing of 52°.

Call Letter	Frequency	GMT From-To
WFK 63	13840 KC/S	1030 - 2200
WFK 70	10750. 5 KC/S	2130 - 2300 0845 - 1100
WFI 57	7849. 5 KC/S	2230 - 0915
WFH 65	5360. 5 KC/S	0300 - 0600 0800 - 0915

(2) Transmission out of New York and beamed toward South America on a mean azimuth bearing of 163°.

Call Letter	Frequency	GMT From	To
WFA 29	9290 KC/S	0000 -	0400
WFA 56	6957. 5 KC/S	0400 -	1000
WFA 29	9290 KC/S	1000 -	1200
WFD 63	13961. 5 KC/S	1200 -	1600
WFD 37	17422. 5 KC/S	1600 -	2200
WFD 63	13961. 5 KC/S	2200 -	2400

(3) Transmission out of San Francisco and beamed toward the Far East on a mean azimuth bearing of 298°. [Presently (early 1964) inactive].

WMH 95	15982. 5 KC/S	2000 -	0345
WMI 50	10190 KC/S	0345 -	0715
WMF 36	6845. 5 KC/S	0715 -	1500
WMI 50	10190 KC/S	1500 -	2000

(4) Part time transmission out of San Francisco and beamed toward the Southwest Pacific on a mean azimuth bearing of 240°.

WMM 49	19715 KC/S	2000 -	0300
WMM 55	15700 KC/S	0300 -	0400
WMM 21	11460 KC/S	0400 -	0900
WMK 27	7340 KC/S	0900 -	1800
WMM 21	11460 KC/S	1800 -	1900
WMM 55	15700 KC/S	1900 -	2000

(Note: Circuit call signs and frequencies are fixed. Schedule of frequencies changes aperiodically as predicted atmospherics dictate. Schedule changes are distributed via the 10204 and 10205 circuits for a three-day period preceding the change and formally through the WMO.)

2. Schedules:

(a) Entered on International Service O TTY Circuits at WBC 1903Z daily.

(b) Entered on fax circuits:

NATL:	2348Z daily
10204:	2243Z daily
10205:	2040Z daily
JQEJA796:	Variable time

3. Code used:

FORMAT FOR TIROS INTERNATIONAL ALERT BULLETIN

(Revised Version)

TB KWBC N (date time group)
TIROS ALERT
PART I 24-48 HR ALERT

$n_o n_o n_o n_o$ YYGGgg $QL_aL_aL_oL_o$ $QL_aL_aL_oL_o$ etc. (Note: A maximum of nine orbits per satellite could be programmed daily).

PART II 7 DAY PLANNING AREAS

YY $QL_aL_aL_oL_o$ $QL_aL_aL_oL_o$ $QL_aL_aL_oL_o$ $QL_aL_aL_oL_o$ etc. (Three areas will be indicated in bulletins transmitted Monday, Wednesday and Friday).

Heading

TB	-	Designator for TIROS Bulletin
US	-	Geographical designator
KWBC	-	International identifier for Weather Bureau Communication Center, Washington
N	-	Indicator for international relay.

Sub-Heading

TIROS	-	Symbolic Word for the Satellite
ALERT	-	Plain language for the message purpose
PART I	-	This part contains 24 - to 48 - hour alert information on the area to be photographed by the satellite.
$n_o n_o n_o n_o$	-	Satellite orbit number in thousands, hundreds, tens and units as proposed in US practice for nephanalyses for TIROS III
YY	-	Day of the month (GCT)
GGgg	-	Time, in hours and minutes GCT of the midpoint of the satellite's pass over the photographed area (also reference REC. 5 of II CSM/WGT).
Q	-	Octant of the globe (WMO Code 3300)
L_aL_a	-	Latitude in whole degrees for picture principal point (Part I) or planning area (Part II).
L_oL_o	-	Longitude in whole degrees for picture principal point (Part I) or planning area (Part II).

PART II

YY	- Day of the month (GCT)
Q	- Octant of the globe (WMO Code 3300)
$L_a L_a$	- Latitude in whole degrees for picture principal point (Part I) or planning area (Part II)
$L_o L_o$	- Longitude in whole degrees for picture principal point (Part I) or planning area (Part II).
Note:	- To prevent misunderstanding when planning area extends into two or more octants, co-ordinates will be given for the north-east corner of the area first, then proceed clockwise.

Sample Message

TB KWBC N 121900Z

TIROS ALERT

PART I

0032	141010	33703	33625	33547
0033	141130	03305	33709	33323
0034	141310	02811	02901	33009
0035	141450	02316	02309	02302
0036	141630	01821	01815	01809
0037	141810	01325	01221	01117
0038	141950	00729	00625	00521
0039	142110	00234	00031	50228

PART II - 7 DAY PLANNING AREAS

21	14040	12136	22660	10280
22	13165	11361	11075	70975
23	22270	20274	20170	71950

A. 2 PHOTOFAX SATELLITE PICTURE TRANSMISSIONS

A limited number of satellite pictures are relayed via the high altitude network each day to stations having photo fax receivers. At present, the only AF receiver is at Sunnyvale -- circuits involved are NASA fax lines connecting CDA stations plus a data link between PMR and Sunnyvale.

A. 3 FACSIMILE NEPHANALYSIS TRANSMISSIONS: CIRCUITS USED

1. Domestic:
   a. National
   b. High Altitude
   c. JQEJA 796 (1R9)
2. Overseas

a. Transmission out of New York and beamed toward Europe on a mean azimuth bearing of 52°.

Call Letter	Frequency	GMT From - To
WFK 63	13840 KC/S	1030 - 2200
WFK 70	10750.5 KC/S	2130 - 2300 0845 - 1100
WFI 57	7849.5 KC/S	2230 - 0915
WFH 65	5360.5 KC/S	0300 - 0600 0800 - 0915

b. Transmission out of New York and beamed toward South America on a mean azimuth bearing of 163°.

WFA 29	9290 KC/S	0000 - 0400
WFA 56	6957.5 KC/S	0400 - 1000
WFA 29	9290 KC/S	1000 - 1200
WFD 63	13961.5 KC/S	1200 - 1600
WFD 37	17422.5 KC/S	1600 2200
WFD 63	13961.5 KC/S	2200 - 2400

c. Transmission out of San Francisco and beamed toward the Far East on a mean azimuth bearing of 298°. (Presently [early 1964] inactive.)

WMH 95	15982.5 KC/S	2000 - 0345
WMI 50	10190 KC/S	0345 - 0715
WMF 36	6845.5 KC/S	0715 - 1500
WMI 50	10190 KC/S	1500 - 2000

d. Part time transmission out of San Francisco and beamed toward the Southwest Pacific on a mean azimuth bearing of 240°.

WMM 49	19715 KC/S	2000 - 0300
WMM 55	15700 KC/S	0300 - 0400
WMM 21	11460 KC/S	0400 - 0900
WMK 27	7340 KC/S	0900 - 1800
WMM 21	11460 KC/S	1800 - 1900
WMM 55	15700 KC/S	1900 - 2000

(Note: Circuit call signs and frequencies are fixed. Schedule of frequencies changes aperiodically as predicted atmospherics dictate. Schedule changes are distributed via the 10204 and 10205 circuits for a three-day period preceding the change and formally through the WMO.)

A.4 CODED (TELETYPE) NEPHANALYSES (NEPAN)

1. Circuits used for dissemination
   a. Civil:
      International Service O TTY Circuits:
      8276, 205T, 233, 235
   b. Military:
      JQECA 506
      JQECW 021
      JQECW 124 (E-W)
      JQECW 013
      JQECW 019/113
      JQBCW 187
      JQBCW 008 (N-S)
2. Schedules
   a. Civil: 00Z plus each 3 hours
   b. Military: Unscheduled
3. Code used:

FORM OF MESSAGE FOR NEPHANALYSIS OF DATA* OBTAINED BY METEOROLOGICAL SATELLITES

1. Explanation

The form of the message for nephanalysis provides for indicating the areas covered by a particular amount, type and description of clouds. A letter of the alphabet is assigned to each unique combination of these three analyzed features, and this letter assignment is maintained throughout the entire message. The letter "A" is assigned to the first combination of features, the letter "B" to the second, the letter "C" to the third, etc. These letters will always be assigned in the following invariable order in the analysis key section of the message; A, B, C, D, F, G, J, K, L, M, N, V, Z, Q, W, E, R, T, Y, U, P, S, H. The specifications for the three characteristic features are given in Code Tables 1, 2 and 3 (see paragraph 4).

---

* Extracted, with updating modifications, from a document marked as "Material proposed for insertion in WMO Publication No. 9, Volume B, Chapter III, under United States National Practices."

The latitude-longitude grid is used to specify the various areas covered by combinations of analyzed features. The basic increment of area used is the one-degree square. In the analysis section of the message, each of these one-degree squares is represented by the letter "A", "B", "C", etc. The analysis key letters assigned to the one-degree squares along one degree bands of latitude are always assembled in the message progressing from west to east. The first coded line in the analysis is always the northernmost one-degree latitude band. Successive latitude bands are encoded from north to south regardless of the octant of the globe in which they occur.

The $QL_aL_aL_oL_o$ group is used to identify the northwest latitude-longitude intersection of the westernmost one-degree square of the first latitude band. The $QL_aL_aL_oL_o$ group will also be used to identify the northwest latitude-longitude intersection of the westernmost one-degree square of each succeeding tenth one-degree band progressing southward. Intermediate latitude bands of one-degree squares will be identified by the L_oL_o indicators only since their relative latitudinal position is defined above.

Normally, data groups for only one latitude band are given per line in the transmitted message. A data group consists of five characters with exception of the L_oL_o indicators. Data groups may contain either numbers or letters or a combination of both with the letter "X" being used as the "fill-in" letter for completing the last data group of a line when necessary. When six or more consecutive identical letters appear along a latitude band of one-degree squares, they may be counted, and this total indicated as "NN" in an optional group (ZZ_rNNN_t) for condensing the message when a reduction in group count would result.

A confidence indicator evaluating geographical accuracy of the information depicted on the nephanalyses is included as the final two characters in the message subheading. The character "C" followed by 1, 2, 3 or 4 will be used for this information. These figures represent the analyst's confidence in the accuracy of the analysis. The figure 1 represents excellent confidence and is associated with geographical placement of position using identifiable landmarks. Figures 2 and 3 represent good and fair confidence, respectively, and are associated with less accurate geographical orientation. Figure 4 represents poor confidence. Normally, coded nephanalyses with this indicator will not be transmitted.

A message will be sent over the Northern Hemisphere Exchange System and other communications channels, as appropriate, at each scheduled transmission time. Some cloud information indicated on the facsimile nephanalysis may be omitted from the coded message when necessary to remain within the capabilities of available communication circuitry. When the meteorological situation warrants and allowable message length is not exceeded, plain language remarks in English amplifying the analysis may be added following the last latitude band of coded information. When for any reason a nephanalysis is not available for transmission at the scheduled time, the message will consist of the communications heading and the word NONE (e.g., AUXX KWBC N YYGGgg NONE).

2. Symbolic Form of Message

Communications Heading	:	AUXX KWBC N YYGGgg
Subheading	:	NEPAN TIROS $n_T n_O n_O n_O n_O$ YYGGgg CN
Analysis Key	:	$AAC_a C_t C_d$ $BBC_a C_t C_d$ $CCC_a C_t C_d$ ... etc.
Analysis	:	$QL_a L_a L_o L_o$ ZZZZZ .... etc.
		(The ZZZZZ groups may be replaced by or intermingled with $ZZ_r NNN_t$ groups in any line when a reduction in group count would result.)
(2d-9th latitude bands inclusive)	:	$L_o L_o$ ZZZZZ (and/or $ZZ_r NNN_t$)... etc.
(10th latitude band)	:	$OL_a L_a L_o L_o$ ZZZZZ (and/or $ZZ_r NNN_t$... etc.

(11th-19th latitude bands same format as 2d-9th latitude bands)

Message continues ....

3. Definitions

a. Subheading

NEPAN	-	Symbolic word for nephanalysis.
TIROS	-	Symbolic word identifying the type of satellite from which the data are obtained.
n_T	-	Number of the satellite from which the data are obtained (in units, e.g., 1, 2, 3, etc.).
$n_O n_O n_O n_O$	-	Number of the satellite pass (in thousands, hundreds, tens and units; e.g., 0001, 0002, 0003, etc.) during which photographs used in this analysis were taken.
YY	-	Day of the month (GCT) on which the photographs used in this analysis were taken.

GGgg - Time, in hours and minutes (GCT), of the midpoint of the pass of the satellite over the photographed area.

(Note: The definitions given here are for the YYGGgg group given in the sub-heading. The YYGGgg group in the communications heading is defined according to Res. 14 (E. C. XIII).

CN - Confidence in accuracy of geographical location of cloud features described by "N" when "N" is:

1 - Excellent

2 - Good

3 - Fair

4 - Poor (not normally used)

b. Analysis Key

AA, BB, CC, etc. - Letter designators assigned to the combinations of analyzed features specified by C_a, C_t and C_d in the same analysis key group. These assignments are valid throughout the entire message. Double letters are used in the analysis key section for confirmation.

C_a - Amount of cloud in a one-degree square (Code Table 1).

C_t - Type of cloud in a one-degree square (Code Table 2).

C_d - Description of cloud in a one-degree square (Code Table 3).

c. Analysis Section

Q - Octant of the Globe (WMO Code 3300).

L_aL_a - Latitude in whole degrees.

L_oL_o - Longitude in whole degrees. (The hundreds digit is omitted for longitude 100° through 180°.)

Z - Letter designator (e.g., A, B, C, etc.) that has been assigned to a combination of analyzed features for the one-degree squares specified.

X - "No data" indicator used to complete the last five character group of a line when required. "No data" indicators may also be used in the ZZ_rNNN_t group along latitude bands in the concavity between areas of the nephanalysis.

ZZ_rNNN_t - Optional group.

Z - Letter designator (e.g., A, B, C. etc.) that has been assigned to a combination of analyzed features for the number of one-degree squares specified by NN (see below).

Z_r - A repeat of the above letter designator for confirmation.

NN - The total number of consecutive identical letter designators along a latitude band of one-degree squares.

N_t - The sum of the two digits (N + N); e.g., AA246 where 6 acts as confirmation for the two digits making up NN. When the sum of these digits is greater than 9, only the final figure of the total will be entered; e.g., when sum is 10 enter 0, when 11 enter 1, etc.

4. Code Tables

Code Table 1

C_a = Amount of Cloud

Code Figure		Amount of Cloud
0	-	Clear or Cloudless
1	-	Mostly Open (MOP)(20-50%)
2	-	Mostly Covered (MCO) (50-80%)
3	-	Completely Covered
4	-	Open (O) (< 20%)
5	-	[Not presently assigned]
6	-	Covered (C) (> 80%)
7		
8		
9		

Code Table 2

C_t = Type of Cloud

Code Figure		Type of Cloud
0	-	None
1	-	Cumuliform
2	-	Stratiform
3	-	Cirriform
4	-	Cumuliform and Cirriform
5	-	Cumuliform and Stratiform
6	-	Cumulonimbus (more or less isolated)
7	-	Cumulonimbus (imbedded in other cloud forms)
8	-	Frontal (chaotically mixed types)
9	-	Unknown

Code Table 3

C_d = Description of Cloud

Code Figure		Description of Cloud
0	-	None
1	-	Thin
2	-	Heavy (dense)
3	-	Possible haze, snow, etc.
4	-	Convective cullular
5	-	Bands
6	-	Transverse bands
7	-	Frontal
8	-	Heavy frontal
9	-	Vortex

5. Example

A coded example in the form in which it is transmitted on the Northern Hemisphere Exchange Network is given for illustration purposes. The data used in this example were obtained from TIROS III on 11 September 1961, but have been converted to 1964 "Amount of Cloud" designaters. Figure A-1 contains the coded message as transmitted. It will be noted that 12 letters have been assigned to combinations of analyzed features in the analysis key (i. e., A, B, C, D, F, G, J, K, L, M, N and V).

Figure A-2 shows the satellite nephanalysis as prepared for facsimile transmission.

Figure A-3 shows the assignment of analysis key letters to the various features of the nephanalysis.

Figure A-4 illustrates the decoded message by showing the analysis key letters assigned to the one-degree squares entered in those squares.

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```
AUXX KWBC N 120410
NEPAN TIROS 30880 111829 C2
AA000 BB110 CC130 DD231 FF210 GG262
JJ310 KK312 LL350 MM319 NN320 VV510
05175 LL066
75 LL099
75 LL134
75 LL167
75 LL178
75 LL099 AALLL LLLLX
75 LL066 AA066 FFFFL LLXXX
75 AA077 NAAAA FFFFF FFFLX
75 AA077 NNNAA FFFFF FFFLL
75 AAAAA NN066 AFFFF FFFFL FLLXX
04175 AAANN NAAAA AAFFF FFFFL LFFFL
75 AA077 FF101 LLLFF FFFFF
75 AA077 FF213
73 AAAAA FF224
70 AAFFF FF202
68 FFFCC CCFFF FF123 KFXXX
67 FFCCC CCCCC FCCCC FFBKF KFFFX
65 FCCCC CCCCC GGGBB KFKKK KKKXX
64 GG112 BBKFK KK077
63 GG088 BBBKF KKKKK KKKFF
03162 BBGGG GGBBB KFKKK MKKKK KFFXX
61 BBBBG GBBBB KFKKK KKKKK FFFXX
60 BB101 KFKKK KKKKF FFXXX
58 BB099 KKKKK BKAAF FFXXX
56 BB123 KAAAF FFBXX
54 BB101 AAAAF FFFBX
53 BB088 AFFAA FFFFB BBXXX
52 BBBBF BBAFA AAFFA AFJBB
50 FFFFA FJAAA AAJJJ JJJBX
49 FBBAA JAAAA JJJJJ JJBBX
02148 BAAJA AVVVF AAAJJ JBBBB
47 AAJDK VVFKK KAAJJ BBBBX
46 AJDKV FKKKK KAAJB BBBBX
45 JDKVK FKKKK KAABB BBBBX
44 DKVFF KKKKF AABBB BBBXX
43 KVFKK KMKFB AABBB BBXXX
43 KK077 FFBAB BBBBB
42 KK066 FFBAB BBBBB
41 KKKKV FFBAB BBBBB
41 VVVVV FFBBB BBBBB
01140 VVVVF FBBBB BBBBX
40 VVVFF FBBBB BBBXX
35 FFFFB BBBXX
```

Fig. A-1 Example of a Coded Message as Transmitted

Fig. A-2 Satellite Nephanalysis as Prepared for Facsimile Transmission

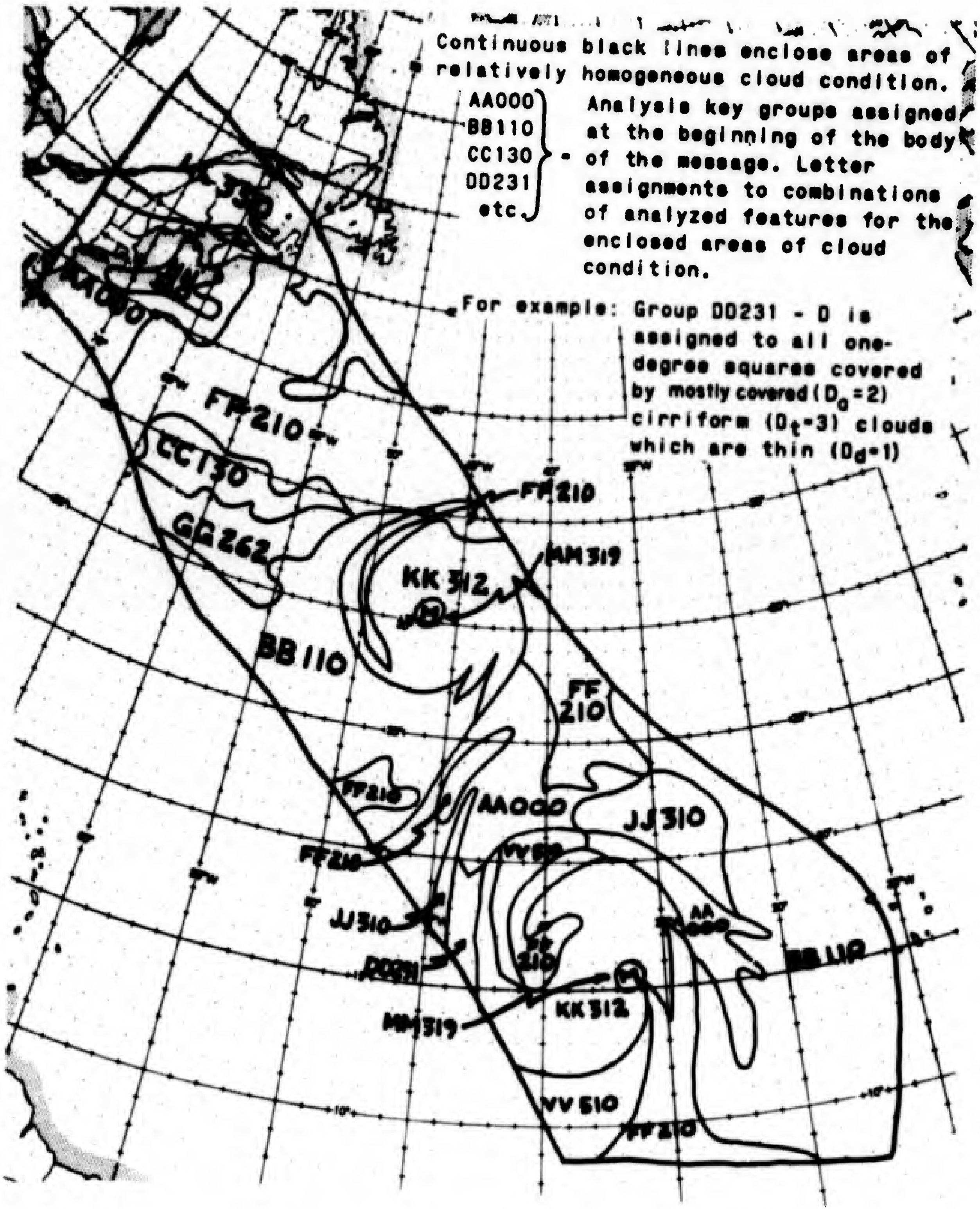

Fig A-3 Example of Nephanalysis Prepared for Encoding

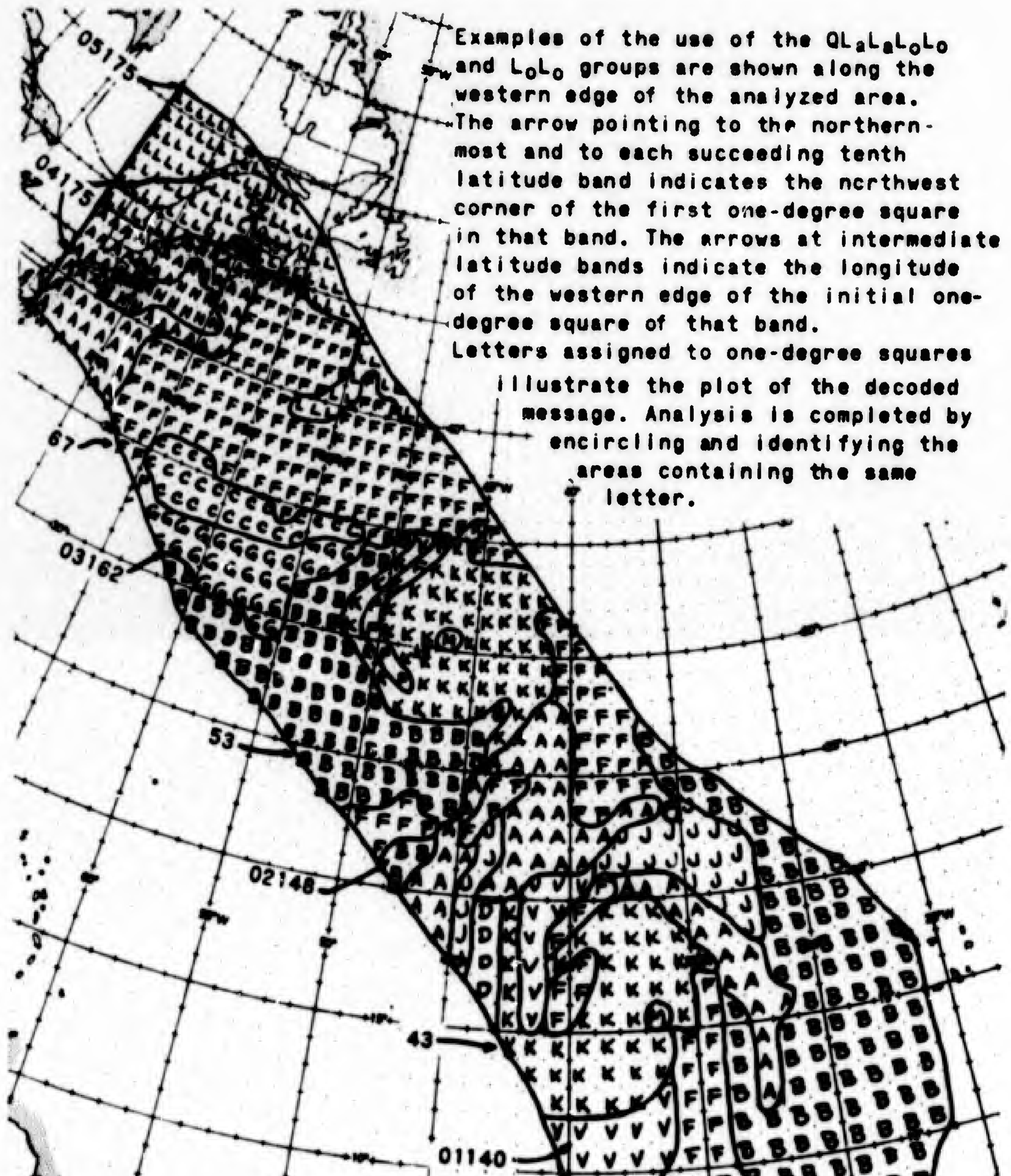

Fig. A-4 Example of Decoded Message

SPARSE DATA REGIONS

APPENDIX B

AN APPLICATION OF TIROS CLOUD OBSERVATIONS IN SPARSE DATA REGIONS

Major Forrest R. Miller

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AN APPLICATION OF TIROS CLOUD OBSERVATIONS IN SPARSE DATA REGIONS [1]

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[Manuscript received April 5, 1963, revised July 8, 1963]

ABSTRACT

The streaming appearance of the earth's cloud cover is strikingly evident from TIROS photographs suggesting that broadscale synoptic patterns in the form of major troughs and ridges can be deduced. Several case studies were made to determine the feasibility of deducing from TIROS nephanalyses and photos major flow patterns at 500 mb. by applying kinematic analysis techniques. Streamline and isotach analyses were inferred from nephanalyses without prior knowledge of the actual synoptic situations. Results show that a reasonable estimate of 500-mb. large-scale synoptic patterns can often be obtained. When deduced flow directions and speeds, and estimated central heights of vortices are introduced into a numerical analysis computer program, using as the first guess over a sparse data region the 500-mb. monthly mean heights, definitive contour analyses are obtained.

1. INTRODUCTION

In 1926 Sir Napier Shaw [9] wrote ". . . we must refer to clouds as being one of the most obvious sources of information about the free air". However, because cloud forms have been primarily classified according to recognizable shapes and textures, little was ever observed or reported about their alignment relative to the wind after the era of the nephoscope. Thus, until recently, the opinion prevailed that a relatively small portion of the earth's cloud cover exhibited banded or striated forms along the flow. Exceptions to this situation, of course, were recognized to exist in the vicinity of well organized cyclones, along jet streams, and in the trade wind belt.

The first photographs from rockets launched over southwestern United States showed definite cloud "streets" [5]. Almost all earth viewing photographs from satellites have revealed the great streakiness of cloud systems [1, 4, 6, 8, 13]. Large masses of stratiform clouds as well as cumuliform clouds, at multiple levels, have shown internal elongated and banded structures in TIROS photographs.

The "streaming" appearance of the earth's cloud cover is strikingly evident when mosaics of TIROS photographs are displayed. A TIROS composite covering the Southern Hemisphere oceans presented by Oliver [6] dramatically pictures the immense cyclonic vortices associated with the "roaring forties". The general sense of large-scale atmospheric motion is evident in such portrayals suggesting that some form of synoptic patterns in terms of major troughs and ridges can be deduced. Even the absence of widespread middle and high level cloudiness over certain regions can be meaningful synoptically if viewed in conjunction with large cloud masses which can be interpreted.

Since TIROS II was placed into orbit, the quality of nephanalyses from satellite readout stations has improved markedly. Although there is no substitute for rectified TIROS photographs in mosaic form, facsimile transmitted nephanalyses have provided meteorologists with excellent supplementary and timely information about the upper atmosphere, particularly over sparse data regions. The problem of finding a suitable procedure for estimating upper-level flow patterns on a global scale from TIROS data over sparse data regions is indeed challenging.

2. METHOD

Several case studies have been made using TIROS cloud data which were received in the form of nephanalyses transmitted by facsimile from the readout sites. Whenever TIROS cloud photographs were available, they served as additional information for the investigation. The primary objective was to determine the feasibility of deducing from satellite cloud data an estimate of the large-scale upper-air flow patterns over sparse data regions. Kinematic analyses were made over the sparse data regions of the Atlantic and Pacific Oceans where conventional analyses are available.

Nephanalyses consisting of several swaths of TIROS data were transferred to standard upper-air plotting charts. A streamline analysis for the 500-mb. level was then inferred from the patterns of the major cloud masses. For example, where cloud elements indicated marked cycloni-

[1] This work was conducted over a two-year period from May 1960 as part of a study to investigate techniques of applying TIROS data to analysis over sparse data regions.

[2] Former assignment Detachment 51, 1210th Weather Squadron, Air Weather Service, USAF.

cally curved patterns a streamline trough or vortex was drawn. In general, streamlines were drawn along the major axis of cloud bands interpreted to be at the middle and upper levels of the atmosphere. In those regions between troughs and estimated to be under the influence of anticyclonic motion, by virtue of being devoid of identifiable upper-level cloud systems, anticyclonic streamline patterns in the form of ridges or anticyclonic singularities were drawn. Neutral points, corresponding to cols in the pressure field, were located in appropriate places between vortices. Monthly resultant upper wind charts [12] also served as a guide and an analytical control in determining the proper streamline patterns and placement of centers, particularly in regions adjacent to but not covered by the nephanalysis. The 500-mb. level was chosen as the analysis level because it represents a middle level in the atmosphere and the derived kinematic analysis could be introduced into the 500-mb. numerical analysis program at the National Meteorological Center (NMC), Suitland, Md.

An isotach field was constructed over the streamlines by applying isotach models since the cloud patterns do not directly reflect the speed distribution. The models were based on sound kinematic principles and empirical relationships between synoptic cloud patterns and the wind field. For example, minimum speed centers coincide with streamline vortices and major axes of maximum speed centers are generally oriented along the upper-level flow. The speed maxima in the westerlies are found aloft to the north of surface positions of the polar front in the Northern Hemisphere.

Although an application of kinematic analysis in this manner is subjective, a series of tests demonstrated that several skilled analysts agreed on the broad-scale streamline interpretation of a particular nephanalysis. The most subjective part of this approach was obtaining a representative speed field which was consistent with both the streamlines and TIROS cloud data. In order to make a reasonable estimate of the speed field, a type of analog system was used. The technique applied was to find in the daily historical map series upper-air height patterns at 500 mb. which were similar to those deduced from the nephanalyses. Several analogous situations were examined and a typical speed pattern was obtained. The derived isotach pattern was superimposed over and adjusted to the streamlines. To complete the analysis, estimates of 500-mb. heights for the cyclonic and anticyclonic streamline centers were obtained from the analog situations in the historical file.

Two series covering analyses of three or more days are discussed in which this method was used. In addition, a single streamline-nephanalysis is shown to illustrate that large-scale cloud patterns reflect circulation changes with time as well as in space. In all of the situations investigated by this method, conventional surface and upper-air analyses were not known or consulted in any way prior to performing the streamline-isotach analyses. The only data referenced during the analysis period were the nephanalyses for each situation, the Weather Bureau's monthly normal charts [10] and 500-mb. streamlines of mean resultant winds [12].

The streamlines and isotachs shown in the figures of this text are the solid curves (with arrows) and dashed lines respectively. Isotach patterns are displayed on only the single nephanalyses of figure 1 and the last charts of the two series described in sections 5 and 6.

The general intent in this paper has been to apply streamline models, based on experience, which are more applicable to the lower 30,000 ft. of the atmosphere. For example, anticyclonic vortices generally show some outdraft characteristic while cyclones are characterized by streamlines spiraling in toward the center. Since it is not possible to determine the rate of inflow or outflow near the center of vortices from TIROS photos, the following procedure was used to illustrate schematically systems in various stages of development. In some analyses the streamline spiraling into the center of a 500-mb. cyclonic vortex have been somewhat exaggerated to give the impression of a system in an accelerating or developing stage. In other cases the amount of streamline convergence was reduced where it was deduced that the system was in a mature or decaying stage. The same general outflow characteristic was given to all anticyclonic vortices. However, even though there were definite uncertainties about the rate of spiraling of the streamlines near the centers, the derived winds yielded numerical analyses comparable to NMC analyses based on radiosonde data.

Detailed composite cloud photographs for the situations described were not available for inclusion. Originals and copies of TIROS 35-mm. films covering each orbit shown by the nephanalyses in this paper are on file at the National Weather Satellite Center, Washington, D.C.

3. ASSUMPTIONS

In this work the primary effort was directed toward deducing from TIROS cloud data, the main trough and ridge patterns of the middle troposphere. There has been no attempt to interpret small-scale synoptic features from the cloud patterns. It is realised that many TIROS cloud photographs exhibit some internal banded structures transverse to flow through the middle levels and lines of cumulus elements paralleling a shear vector of the winds in the convective level. However, the assumptions presented below are considered reasonably valid when applied to macro-scale weather and flow patterns:

a. The orientation and distribution of major cloud masses reflect the broad-scale flow of the atmosphere. From striated patterns and elongated elements or "fingers" of clouds the general direction of flow can be inferred.

b. In regions lacking extensive masses of stratiform, middle, and high clouds and showing only small-scale cumulus, the flow is generally assumed to be associated with large-scale anticyclonic circulations within limits, namely: the placement of a ridge or anticyclone center under such circumstances is dependent on the estimated positions of troughs inferred where clouds are present and the expected climatological positions of the subtropical anticyclones.

c. Broadscale synoptic patterns as interpreted from TIROS upper-level cloud patterns are fairly representative of the flow throughout a deep layer, i.e., above the convective levels and below the cirrus levels. This assumption implies that macro-scale flow patterns exhibit relatively small directional shears within the middle layers.

d. Major cloud masses of the upper and middle troposphere can, in a very general way, be distinguished from low-level clouds. New techniques now under development for analyzing TIROS infrared data [3] will provide assistance in delineating cloud types and heights.

e. A judicious application of climatology and analog techniques in finding representative isotach patterns is also assumed.

4. TIROS II PHOTOGRAPHED UPPER-AIR CHANGES

A double composite nephanalysis for December 4 and 5, 1960 is shown in figure 1. The composite was originally two separate nephanalyses from December 4 through several hours beyond December 5. In figure 1 broken to overcast stratiform clouds for December 4 are heavily shaded; those observed by TIROS on December 5 are lightly shaded. Originally this composite was color coded. Patches of clouds reported on both days to be scattered to broken are hatched. Cross hatching represents this condition over the same region on both days.[3] This example is included to illustrate how large cloud masses, showing changes in alignment in the photos and nephanalyses, can be interpreted in terms of upper flow patterns. Two prominent areas showing realignment and movement of large cloud masses identifiable on both days are shown in figure 1.

Over northwestern portions of Africa (15° N.–30° N.; 0°–15° E.) major cloud elements were oriented northeast-southwest on December 4. However, by the time TIROS traversed this region again 24 hr. later, these cloud patterns had assumed a more north-south or even northwest-southeast orientation. In contrast, scattered to clear conditions were photographed over the northwestern part of Africa (vicinity of 20° N., 10° W.) on both days. Off the African coast in the Atlantic, large cloud masses in an apparent north-south elongation persisted during the 4th and 5th of December. Undoubtedly some of these coastal cloud masses consisted of low-level stratus on the east side of the Atlantic subtropical anticyclone. However, a definite cyclonic turning of the major cloud elements over Africa (20° N.–35° N.; 5° W.–10° E.) was viewed by TIROS on December 5, particularly to the east of the streamline center of the cyclone. Recent case studies [2, 7, 8] have shown TIROS views of mature cyclones with relatively clear central portions and extensive moisture bands around the periphery.

Thus, the distribution and reorientation of clouds over Africa were interpreted to reflect the formation of a cut-off cold Low with a closed circulation becoming established after December 4. The 500-mb. charts from the National Meteorological Center (NMC) showed a well defined trough moving over the African coast between December 3 and 4. By December 5 (fig. 2), a low-latitude, upper-level cyclone had developed with its center in about the same position as shown by the streamline center over northwestern Africa in figure 1. The 500-mb. low center persisted for several days. It should also be noted that over the Mediterranean Sea, eastern Africa, and Egypt (extreme right of fig. 1), generally clear conditions were reported on the nephanalysis, i.e., no large masses of stratiform clouds were reported. This region was interpreted as being associated with an upper-level ridge as shown by the streamlines.

The other region showing some movement and realignment of cloud masses was over the Atlantic, off the east coast of the United States. Scattered to broken cumulus type clouds were observed along the east coast (20° N.–40° N.; 70° W.–80° W.) on both days. Farther east a broad, overcast band of stratiform clouds oriented north-south marked the leading edge of a frontal zone and associated upper-level trough on December 4 (shown in fig. 1 by the heavy shaded region along 60° W.). On the next day this same band of cloudiness had shifted 5° of longitude eastward between 15° N. and 30° N. and was apparently oriented more nearly northeast-southwest. The northern portion of this cloud mass was not viewed by the TIROS camera on December 5. In the central portion of figure 1 between 15° N. and 30° N., the two days' composite seemed to show a rather random distribution of clouds at first analysis, but a close study indicated that many of the major cloud elements had their major axes elongated in an east-west direction. A general eastward drift and convergence of the cloud masses toward the low center was inferred and is represented by the streamlines. The streamline and isotach analyses in figure 1 were deduced from the composite nephanalysis for December 5, 1960 (the lightly shaded cloud masses). The streamline analysis agreed with the NMC 500-mb. height analysis shown in figure 2. In particular, the placement of the streamline troughs and ridges was in agreement, but their amplitudes were greater in the NMC analysis on December 5. The relatively clear areas along 50° W. and 10° E. to 20° E. were verified to be associated with ridges.

5. STREAMLINE-NEPHANALYSES OF MAY 19–21, 1960

Figure 3 represents a combined streamline-nephanalysis for May 19, 1960. The period covered by the satellite

[3] The system applied to nephanalyses in this report, for reporting amount and types of clouds observed from satellites is described in "Depiction of Satellite Cloud Observations for Facsimile Transmission", *Forecast Development Report* No. 1, U.S. Weather Bureau, Washington, D.C., December 1960, 25 pp.

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Figure 1. - Two-day composite nephanalyses for December 4 and 5, 1960. Streamlines and isotachs in solid and dashed lines respectively represent the deduced flow pattern at 500 mb. for 0000 GMT, December 5, 1960. See text for nephanalysis symbols.

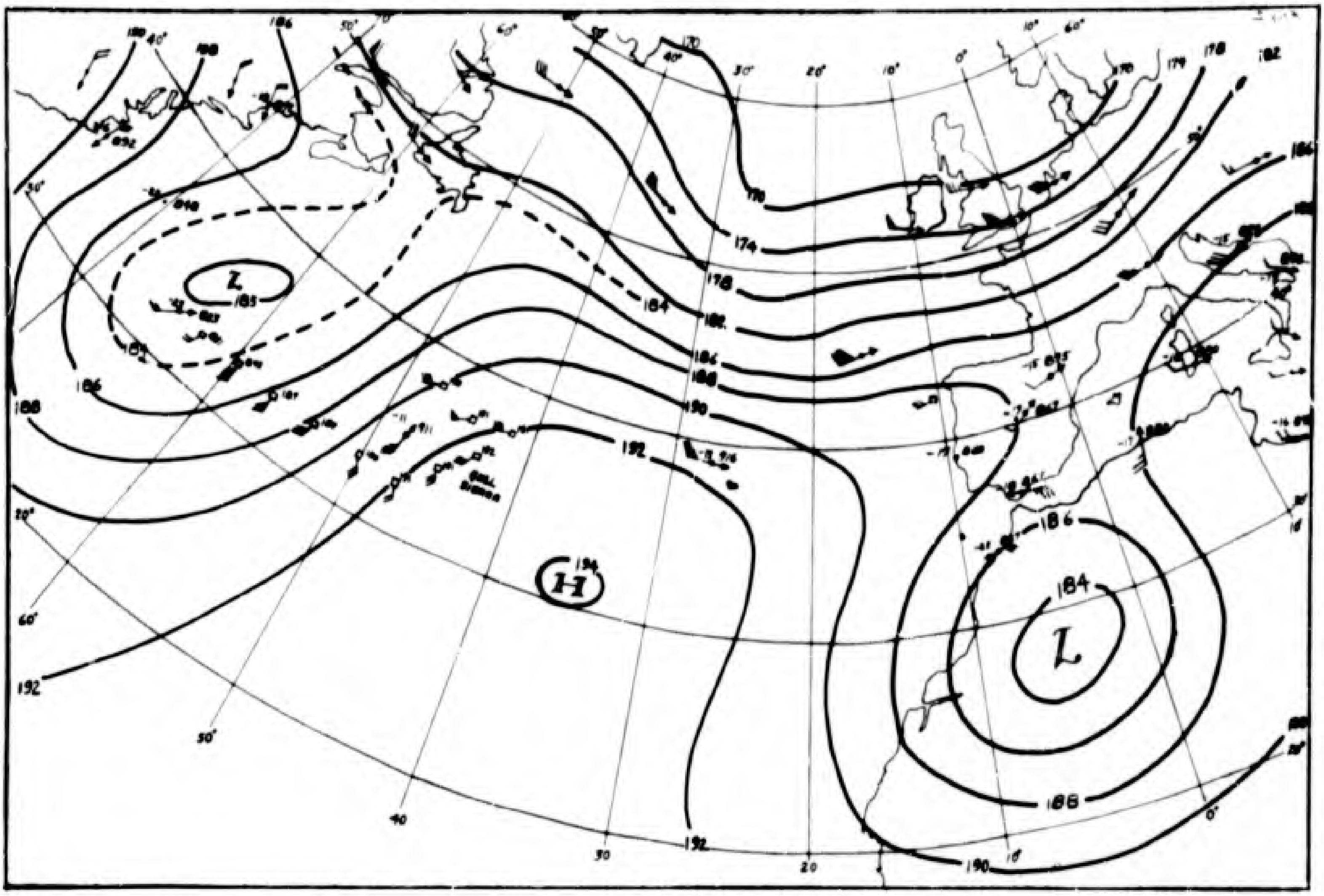

FIGURE 2.—Conventional 500-mb. analysis for 0000 GMT, December 5, 1960 from the National Meteorological Center.

data extends from a few hours before 0000 GMT to a few hours after on May 19. This analysis helped to establish continuity for subsequent analyses on May 20 and 21 shown in figures 4 and 5.

Heavily shaded areas (white on the figure) represent overcast stratiform clouds, and large patches of scattered to broken cumuliform are shown as hatched areas. Light shaded areas (gray) depict scattered to broken stratiform clouds. Few or scattered individual cumulus clouds are represented by the cumulus symbols over a given region. This same delineation scheme is followed in figures 4 and 5. For May 19 (fig. 3) cloud data from only three orbital passes were available. To the north and south of the Pacific region covered by TIROS data, the 500-mb. resultant wind chart [12] for May was referenced in drawing the streamlines. The isotach analysis (dashed lines) is displayed with the streamlines in only the final chart (fig. 5) although originally isotachs were drawn on the other analyses as well. The marked frontal cloud structure of the central Pacific Low shown in figure 3 was interpreted as part of a deepening cyclonic system. The general widespread cloudiness (but banded to some degree) in eastern Asia seemed to be associated with a relatively new system. In the Gulf of Alaska the primary frontal band apparently had moved completely out of the main cyclonic circulation and extended northeastward into Canada. There were some well defined cyclonically turning cloud bands and lines showing a definite trough and the general extent of the cyclonic circulation. Elsewhere between low centers small amounts of stratiform clouds were interpreted to be associated with northwesterly flow.

The nephanalysis for 0000 GMT, May 20, 1960 (fig. 4) showed some reintensification of the front in the eastern Pacific. The heavy frontal cloud bands in the central Pacific revealed an outstanding example of the occluding process with the primary moisture band wrapping up, over, and around the central cyclone. Several scattered "bright" cloud patterns were strung out to the southwest from the polar front over the eastern Pacific. Widespread stratiform clouds continued to prevail over the northwestern Pacific, but a definite banded structure with cyclonic curvature could be discerned.

The streamline neutral points and subtropical anticyclonic centers south of 30° N. latitude in figures 3, 4, and 5 were based on their climatological positions for May at 500 mb. and adjusted to fit the streamline pattern inferred from the nephanalyses.

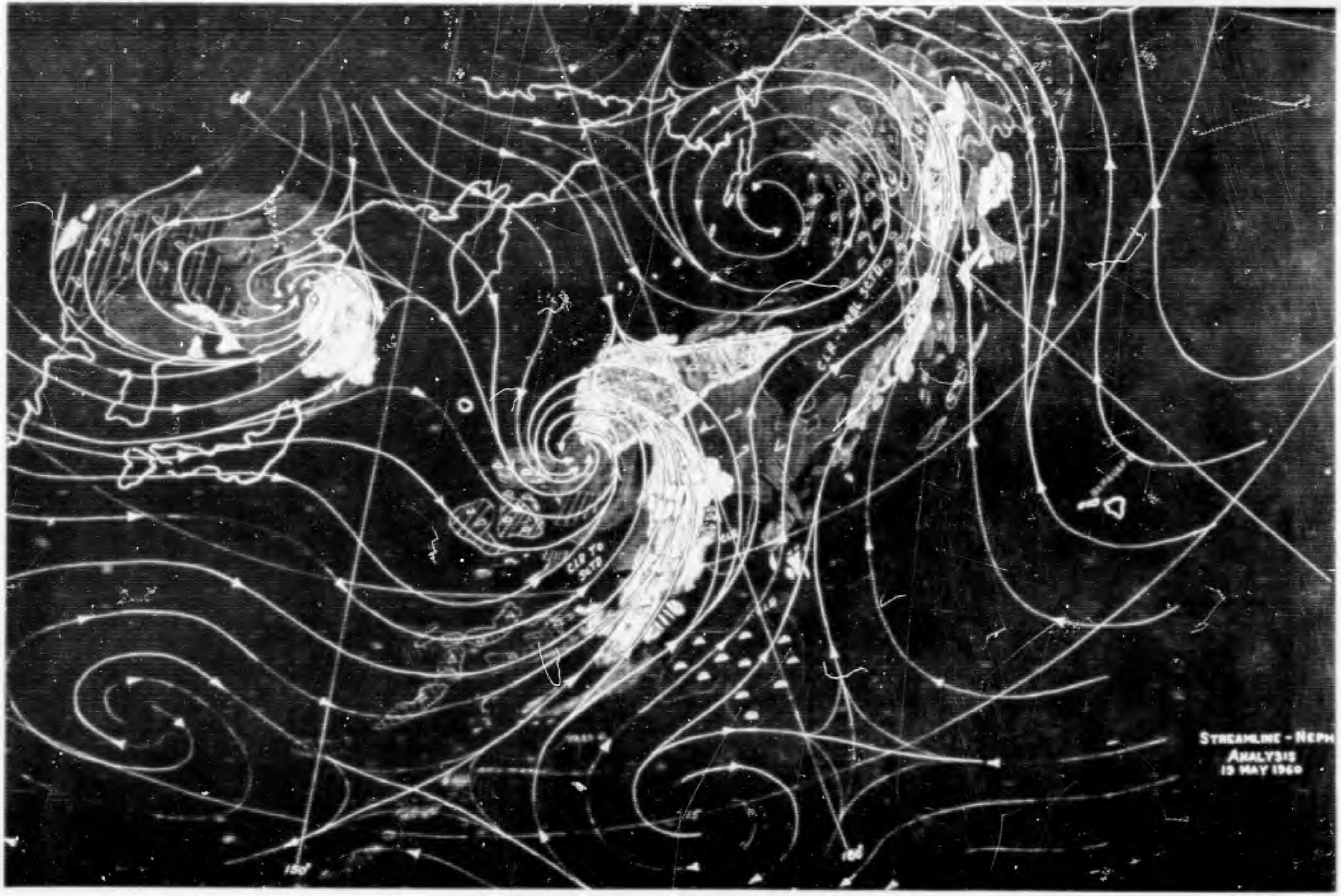

Figure 3. - Streamline-nephanalysis for 0000 GMT, May 19, 1960. White patches depict broken to overcast heavy cloudiness; scattered to broken conditions are shown by gray shading, hatching, and individual symbols. Streamlines shown with arrows represent the 500-mb. flow pattern.

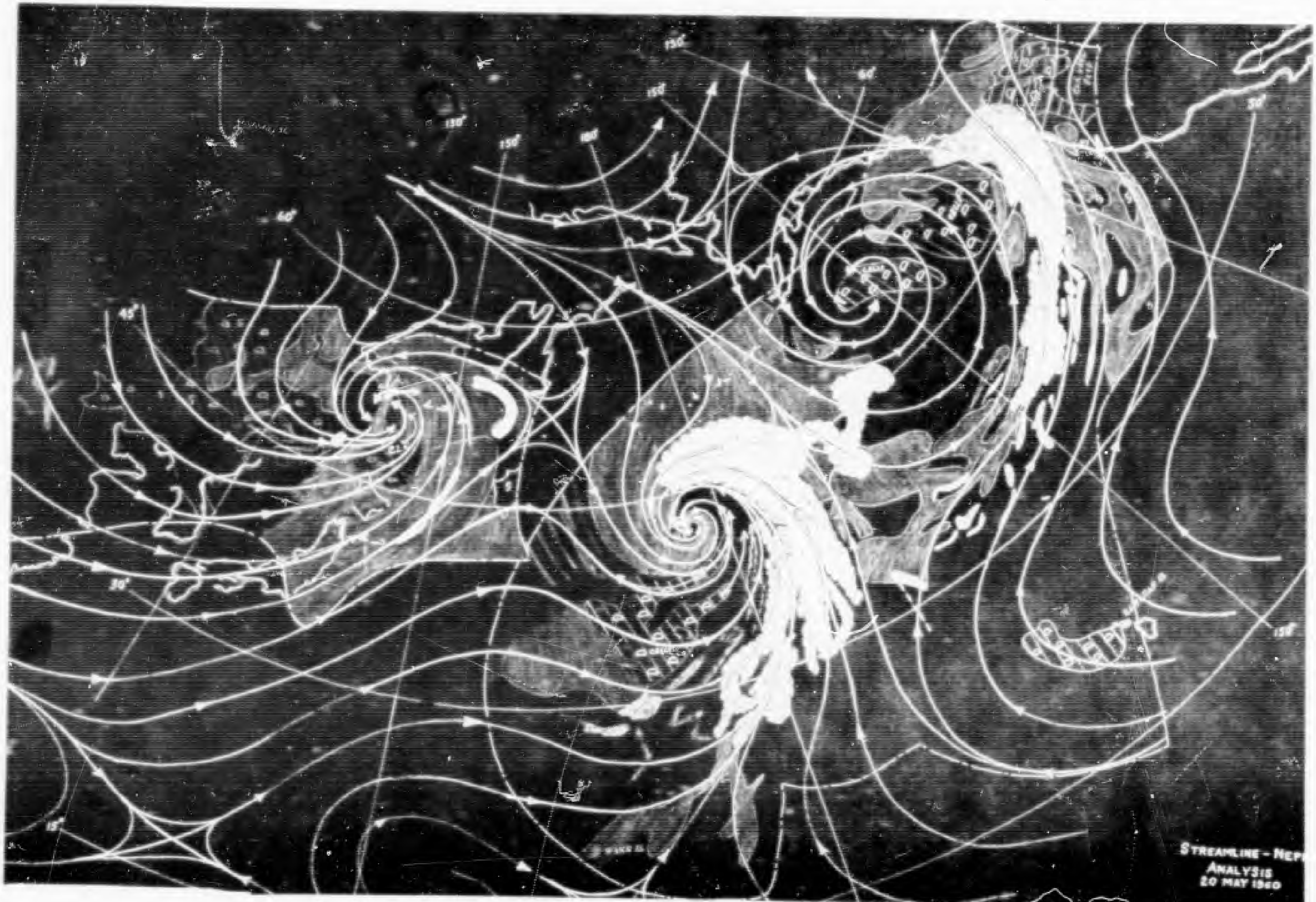

Figure 4. - Streamline-nephanalysis for 0000 GMT, May 20, 1960.

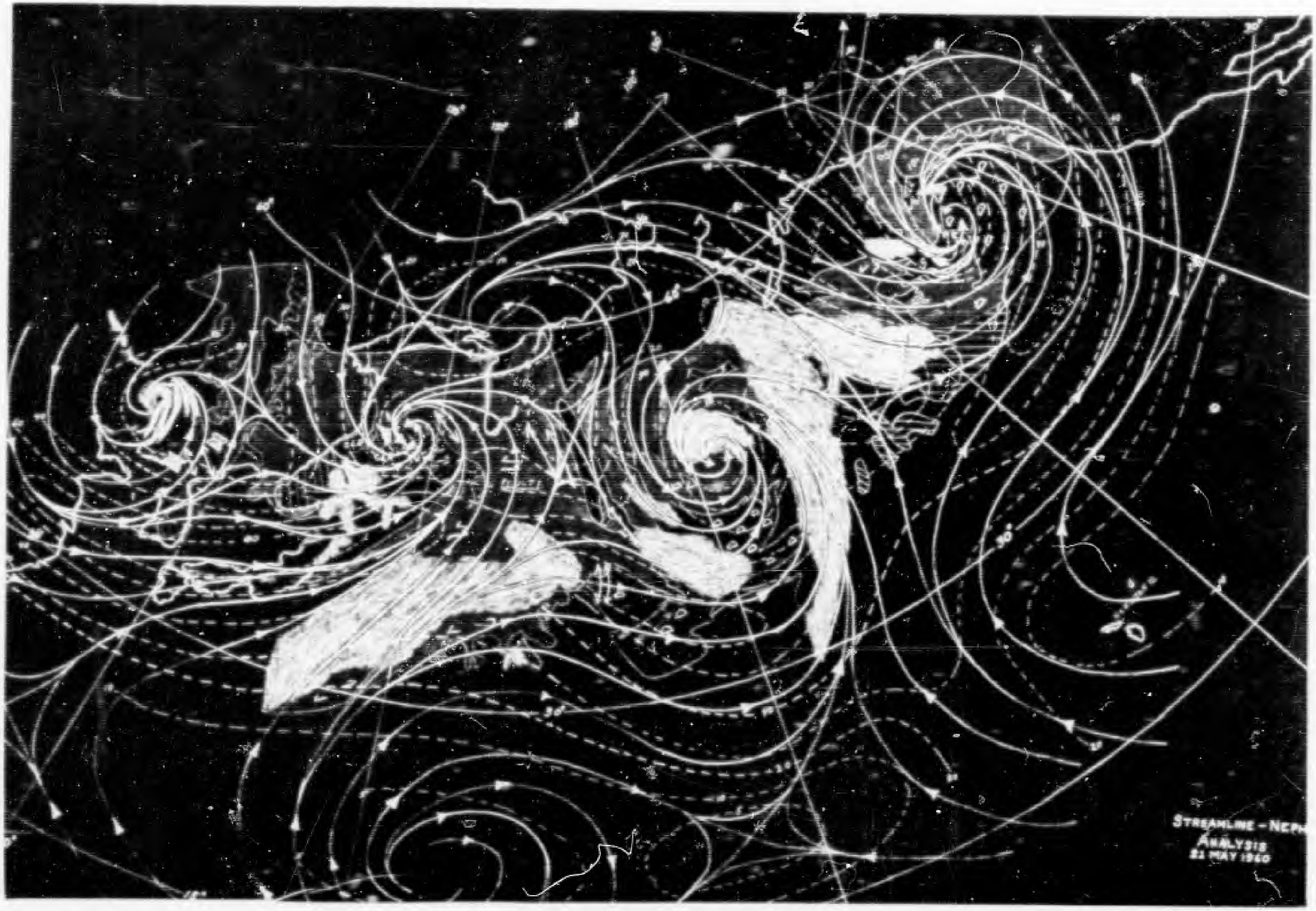

Figure 5. - Streamline-nephanalysis for 0000 GMT, May 21, 1960. Dashed lines are isotachs labeled in knots.

The nephanalysis for 0000 GMT, May 21, 1960 (fig. 5) revealed more widespread cloudiness throughout the central and western Pacific. From this nephanalysis it was concluded that the major portion of the eastern Pacific frontal band moved out from under the satellite track leaving only scattered remnants of the old cyclonic circulation. The heavy cloud pattern in the central Pacific showed the frontal system to be occluded and moving to the northeast away from the upper Low. However, some large cloud masses and other cloud striations around the periphery of the center marked the cyclone's central position. An extensive heavy overcast southeast of Japan was part of a polar frontal system for which there were no TIROS data on the two previous days. This frontal system was later verified from conventional analyses as intensifying under a strong jet on May 21. The main western Pacific 500-mb. low center was over Sakhalin on May 21. There was strong evidence in the banded cloud patterns of a new cyclone circulation over Manchuria developing in the westward extension of the Sakhalin Low. Conventional 500-mb. charts from the National Meteorological Center on May 21 revealed a trough extending southwest into Manchuria. Additional details concerning verification of analyses for this case study are presented in section 7.

The streamline-isotach analyses in figures 3, 4, and 5 represent the 500-mb. flow as deduced from the nephanalyses described above. All three charts show, in some state of intensification or decay, the classical example of the polar front family of waves extending across the Pacific Composites of TIROS photographs from which the nephanalyses of this series have been made up have appeared in several publications [1, 11]; they have become some of the classic examples from the TIROS I series.

6. STREAMLINE-NEPHANALYSIS IN THE PACIFIC, AUGUST 23–25, 1961

The discussion of the May 19–21, 1960 series was based primarily on nephanalyses and TIROS photographs of a well defined family of polar frontal systems in various stages of development over the mid-central Pacific. In order to expand further on the streamline-isotach approach as applied to nephanalyses, the following 4-day series, which covers most of the Pacific Ocean and adjacent land areas, is presented.

This series is based on nephanalyses covering the period August 23 through 25, 1961. During this period TIROS III traversed the Pacific Ocean region from the equator to near 50° N. recording cloud structures of the southeast Asia monsoon and continuing eastward over several large regions of cloudiness over the Pacific and the United States. These nephanalyses are some of the most comprehensive and best documented TIROS series covering the Pacific Ocean region now on record. In most cases the composites cover a period of approximately 10 hr. TIROS III, while on its orbital trajectories over the Pacific and United States, swept through about three passes before midnight and three after midnight of the day designated on each chart of figures 6 through 9. The same cloud shading scheme described in section 5 for the May series was used in this series.

One of the most significant features in figures 6, 7, 8, and 9 of this series, is the widespread band of heavy, stratiform cloudiness between latitudes 35° N. and 50° N. stretching across the North Pacific. Periodic interruptions or elongated breaks in these heavy overcast regions can be seen where data are available on all charts in this belt from China eastward to the west coast of the United States. Many of the heavy cloud areas are characterized by banded elements with apparent cyclonic curvature. The polar front, with periodic breaks in the cloud activity, appears to show up distinctly in all nephanalyses, particularly those of figures 7 and 9. The most marked polar frontal system appears in the nephanalyses between 30° N. and 50° N. from 150° W. to 150° E.

Another outstanding feature common to all charts of this series is the general lack of extensive layers of stratiform middle and high clouds over the Pacific Ocean, eastern China, and southwestern United States between 20° N. and 35° N. Over this same region nephanalyses show orderly lines of cumulus and other singular large cloud elements which can be seen converging, with some anticyclonic curvature, into the main mass of polar front clouds. These elongated narrow lines of clouds, oriented generally southwest to northeast, are particularly prevalent on August 22 and 23 (figs. 6 and 7). On August 22 near 35° N., 136° W. several lines of clouds revealed a previously undetected cyclonic circulation which appeared to be less well defined on August 23.

Since TIROS cloud data were missing over large sections of the Tropics south of 25° N., it was possible to make only generalized deductions about the flow based on cloud structures. Inferences from cloud patterns available tied in with climatology and the analyses over extratropical regions served as the primary guide in estimating the streamline troughs and ridges south of the anticyclonic ridge for the 500-mb. level. In August the 500-mb. level lies well within the easterlies over most regions south of 25° N. Hence, it is possible to estimate a reasonable flow pattern at this level, considering nephanalyses and the situation to the north, without getting involved with the transition (between easterlies and westerlies) zone. However, this is not possible in the spring, fall, and winter seasons [12].

Figure 10 shows the combined 500-mb. and surface analyses for 1200 GMT, August 24, 1961, prepared at the National Meteorological Center. It is apparent from figure 10 that on the 24th a series of polar waves was moving out of Asia and across the Pacific between 35° N. and 50° N. The subtropical ridge was pronounced and extended westward from the United States to China in multi-cellular systems. Southeast of Formosa typhoon Lorna was moving slowly west-northwest.

The typhoon was not detected from the nephanalysis.

Figure 6. - Streamline-nephanalysis for 0000 GMT, August 22, 1961. Heavy broken to overcast cloudiness observed by TIROS III is shown as solid white patches. Scattered to broken cumuliform and stratiform cloudiness are depicted as light gray or hatched areas and by individual symbols. Streamlines shown with arrows represent the 500-mb. flow pattern.

FIGURE 7. Streamline surface analysis for 0000 GMT, August 23, 1961

lines are isotachs labeled in knots.

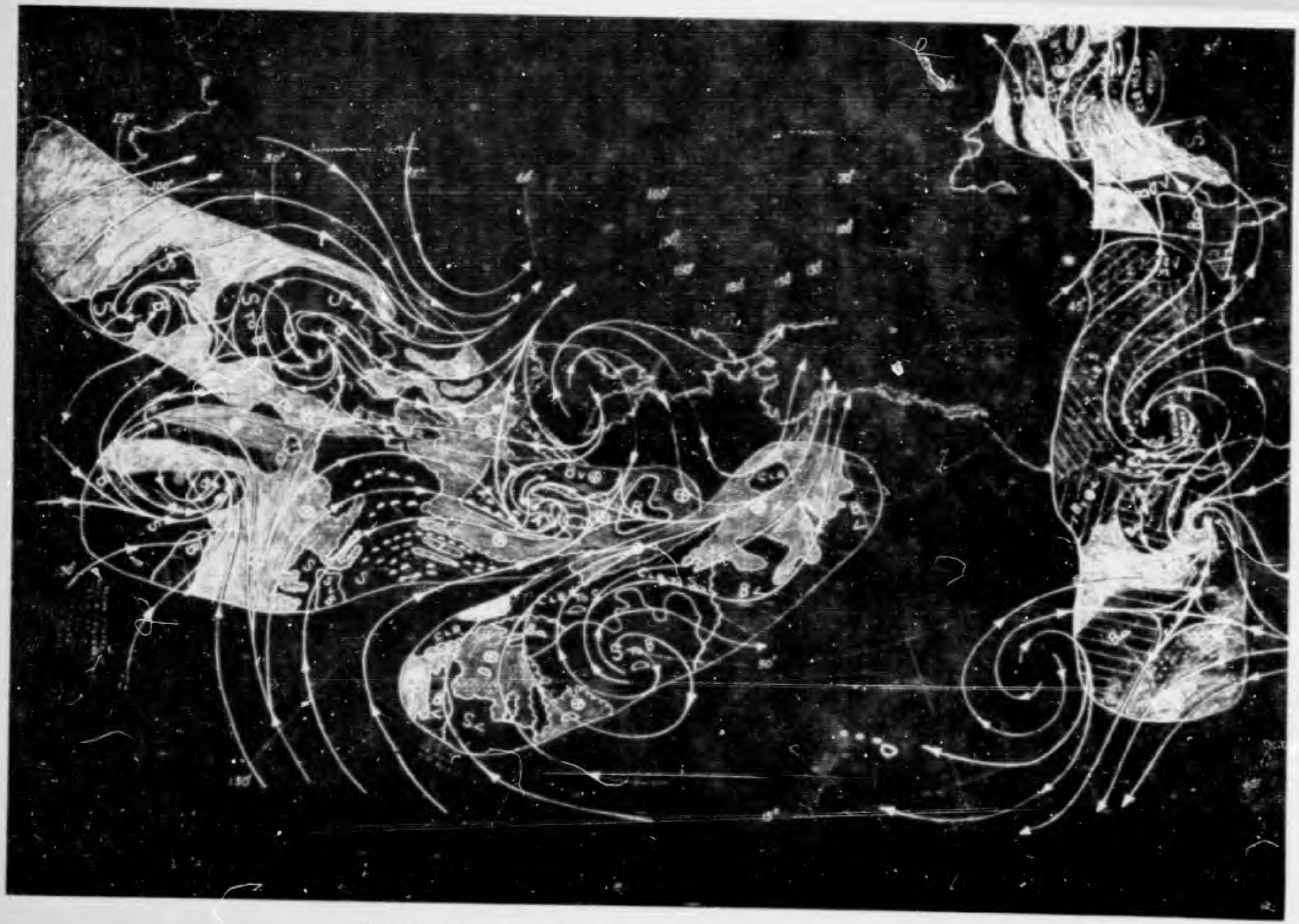

FIGURE 8. Streamline-nephanalysis for 0000 GMT, August 24, 1961.

FIGURE 9. Streamline-nephanalysis for 0000 GMT, August 25, 1961. Dashed lines are isotachs labeled in knots.

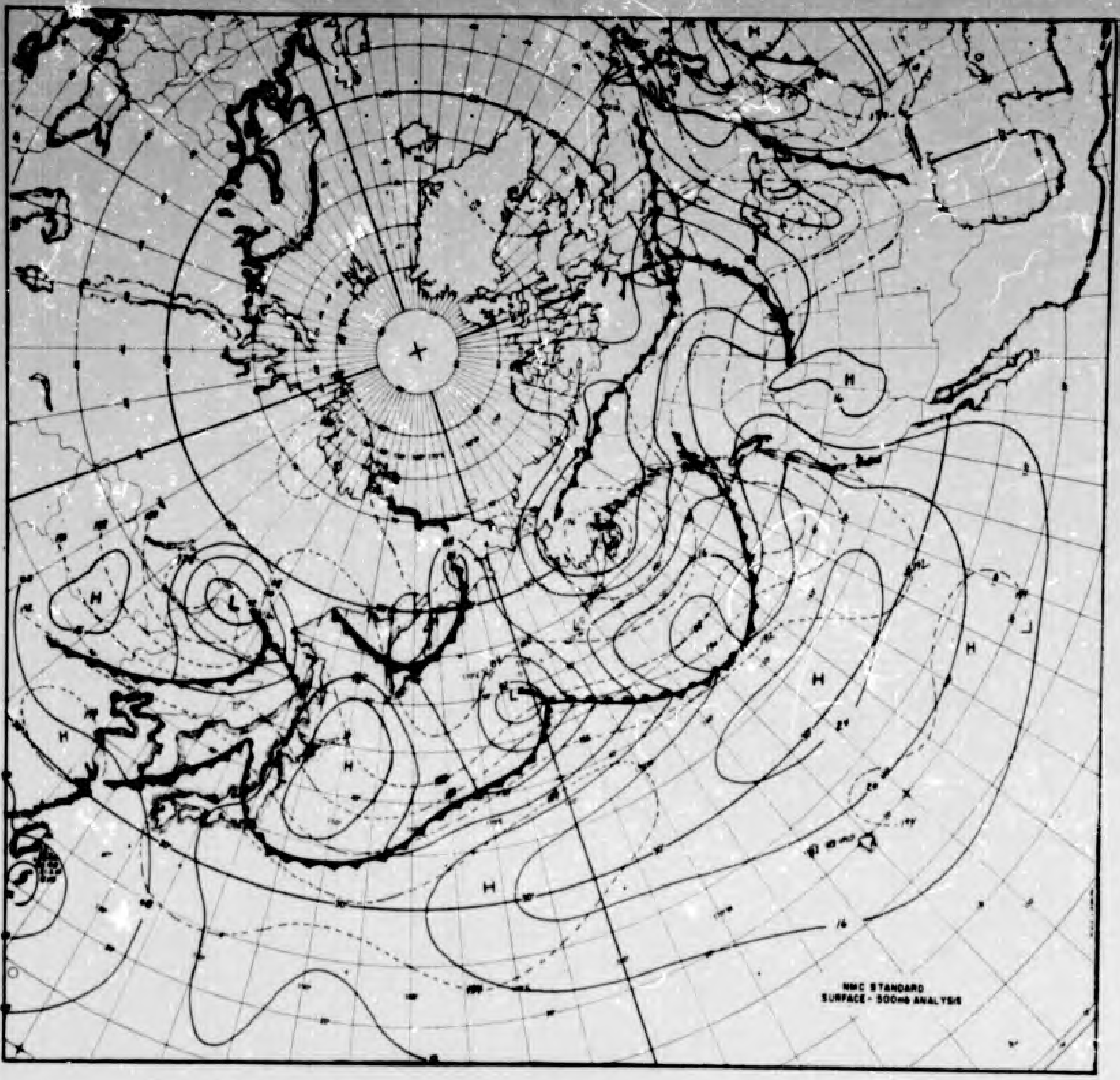

FIGURE 10.—Surface (solid lines) and 500-mb. (dashed lines) chart for 1200 GMT, August 24, 1961.

However, because of the reported heavy cloudiness over the southwestern Pacific, as shown by the nephananlyses in figures 8 and 9, it was assumed that a pronounced tropical cyclone had generated in the vicinity of the Philippine Islands.

The original streamline analyses inferred from the neph-analyses for August 24 and 25 consisted of an easterly wave pattern at 500 mb. over the region north and east of the Philippines. Later when the NMC surface analysis for 0000 GMT, August 25 was reviewed, it was discovered that the assumed tropical disturbance was in fact typhoon Lorna located at an estimated position of 21.2° N., 122.9° E. at 1200 GMT, August 24, 1961. The streamlines were then redrawn, as shown in figures 8 and 9, to fit schematically a typhoon situation. This was done to determine the analytical effect of introducing a wind field and estimated 500-mb. central pressure of a typhoon into the NMC numerical analysis program. The result of the re-analysis is shown in figure 14A. The typhoon symbol in this figure is placed at the center of lowest 500-mb. contour values obtained in the re-analysis. The original NMC 500-mb. numerical analysis, figure 13B, did not reveal a developed tropical cyclone in this region.

7. APPLICATIONS TO NUMERICAL ANALYSIS

Data from several of the streamline-isotach analyses obtained in the manner just described were introduced into the IBM 7090 computer analysis program at the National Meteorological Center.[4] One procedure was to assume that the only data available for a 500-mb. analysis were monthly normal 500-mb. heights punched on cards and the streamline-nephanalyses. The 500-mb. normal heights were obtained from the Extended Forecast Branch of NMC and served as a first guess field for the numerical analysis. Wind directions and speeds were extracted at even 10° latitude and longitude intersections from the deduced kinematic analyses to provide the additional data required for the numerical re-analyses. These data together with the estimated 500-mb. heights of the centers of vortices were punched on cards according to a specified format. The cards were then introduced into a single run of the NMC computer program and the first guess field was modified to conform with the input data.

THE MAY 1960 CASE

For the May 1960 series described in section 5, the 500-mb. May normal heights were used as a first guess field. A contour print-out of this field for the region north of the subtropical ridge is shown in figure 11 to illustrate just how uninformative a 500-mb. normal contour chart can be for estimating the synoptic situation.

The North Pacific region outlined by the heavy lines in figures 11 and 12A shows the 500-mb. re-analysis region. Figure 12A shows the results obtained after applying the wind data and estimated heights for 0000 GMT, May 21, 1960 (fig. 5). The fronts superimposed over the 500-mb. re-analysis were taken from the NMC surface chart for 0000 GMT, May 21, 1960. The dashed lines in figure 12A show the positions of the troughs and ridges of the NMC 500-mb. numerical analysis.

In addition to the pronounced definitive changes from the first guess normal field within the area outlined by the heavy line, there are several significant features worthy of note. First, the position of the belt of maximum westerlies and the low pressure centers, as shown by the re-analyzed contours of figure 12A, are in close agreement with the NMC analysis (fig. 12B) made with conventional data. Secondly, the major trough and ridge lines are in agreement with those in figure 12B, except for the trough line off the west coast of the United States.[5] Outside the region of re-analysis, west of 100° E. and east of 90° W. the May normal contours were only slightly modified; inside the region the pattern was considerably modified and specified the synoptic situation reasonably well.

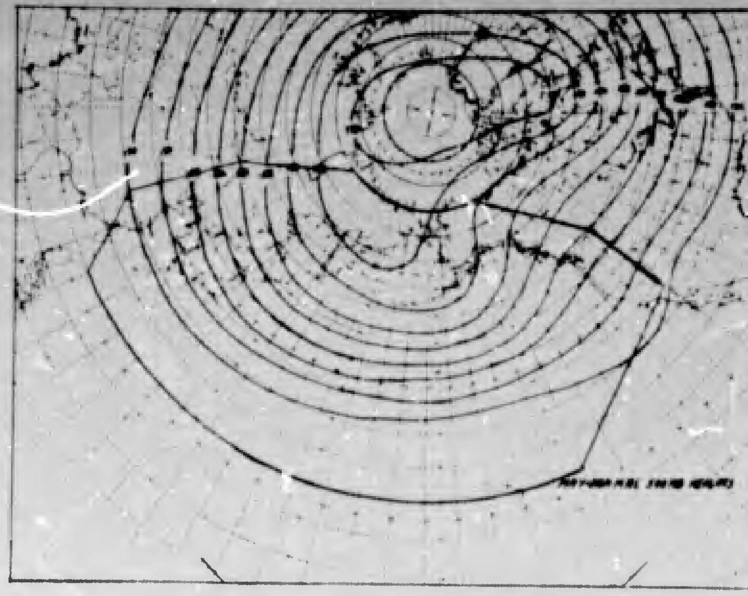

FIGURE 11.—500-mb. monthly normal heights for May.

THE AUGUST 1961 CASE

A numerical re-analysis was also made of the August 25, 1961 situation shown in figure 9. In this case, it was assumed that the latest data available for a first guess were the NMC 48-hr. numerical forecast for 500 mb., displayed in figure 13A. The final re-analysis based on the nephanalyses and streamlines is shown in figure 14A, and the NMC numerical analysis used for verification is displayed in figure 13B. As a result of introducing data from the kinematic analysis a definite improvement over the first guess 48-hr. forecast was obtained in some areas: the trough over the central United States was better positioned; the low center off the Aleutian Islands was better defined; and some improvement in the positioning and definition of the subtropical ridge of the Pacific can be seen. The position and intensity of the belt of maximum westerlies over the North Pacific was also better defined by the re-analysis. The 500-mb. low center of the typhoon north of Luzon, P.I. was introduced into the re-analysis as described in section 6. However, the center, as determined by the lowest contour heights, was south of the reported position. The 24-hr. barotropic forecast shown in figure 14B was obtained from the re-analysis (fig. 14A). This forecast revealed that the wind and 500-mb. height data introduced to obtain the re-analysis was satisfactory for the NMC barotropic forecast model.[6] It should be pointed out here that in order to produce a reasonable numerical contour analysis from a 500-mb. monthly normal first guess, some estimate of the height at each center of action was required as well as the wind data.

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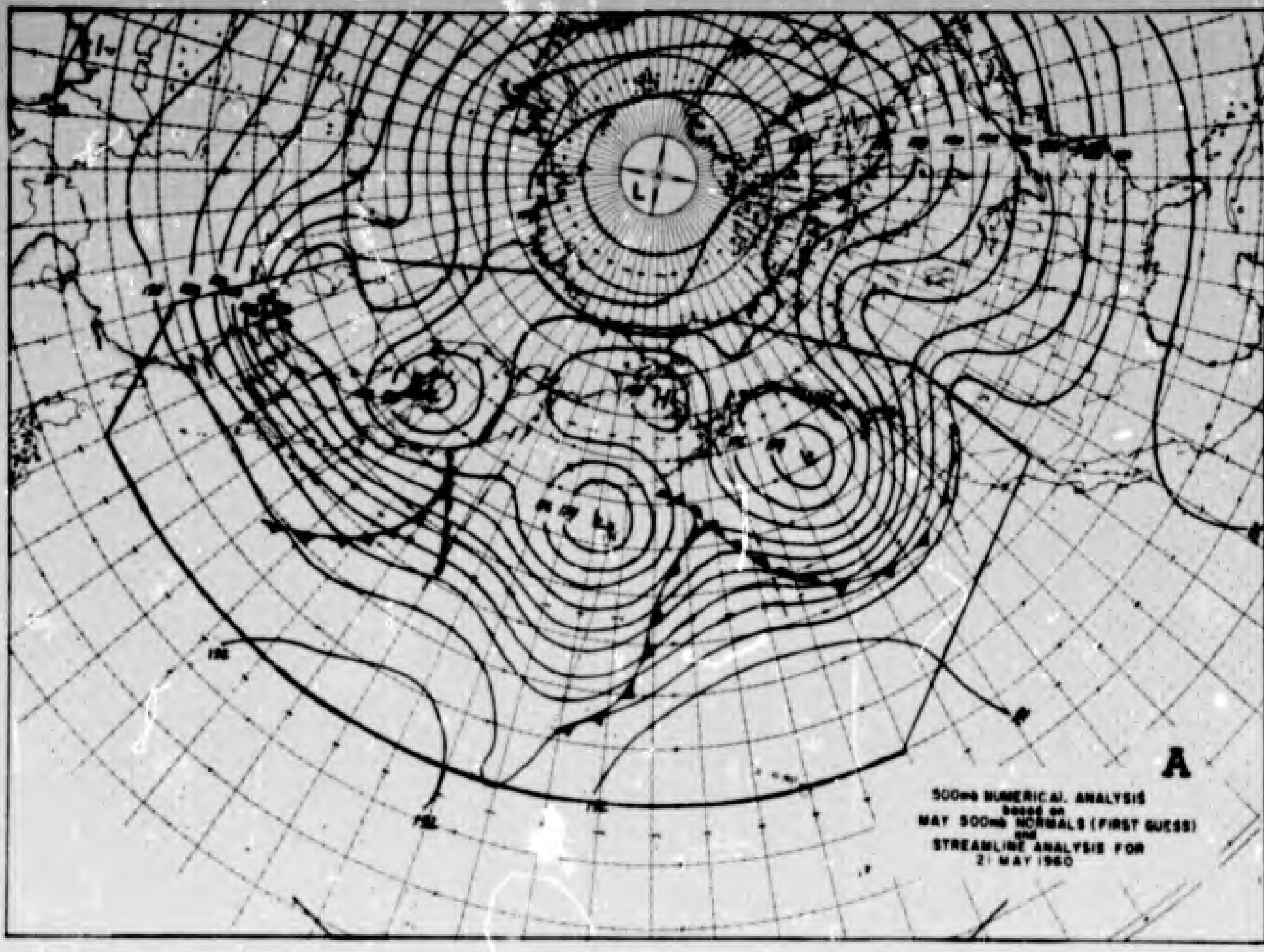
[4] The NMC analysis program requires height values for each of the 1977 grid points to be used as a first guess. The program will accept both winds and heights as additional data for any desired region within the grid to be analyzed.

[5] A post analysis revealed that the west coast trough in figure 12B could have had a position farther west on the 21st. This would have given a more uniform movement of the trough from May 20 to May 22, 1960.

[6] The troughs and ridges remained well positioned and the typhoon circulation was forecast in the correct direction but at too slow a speed.



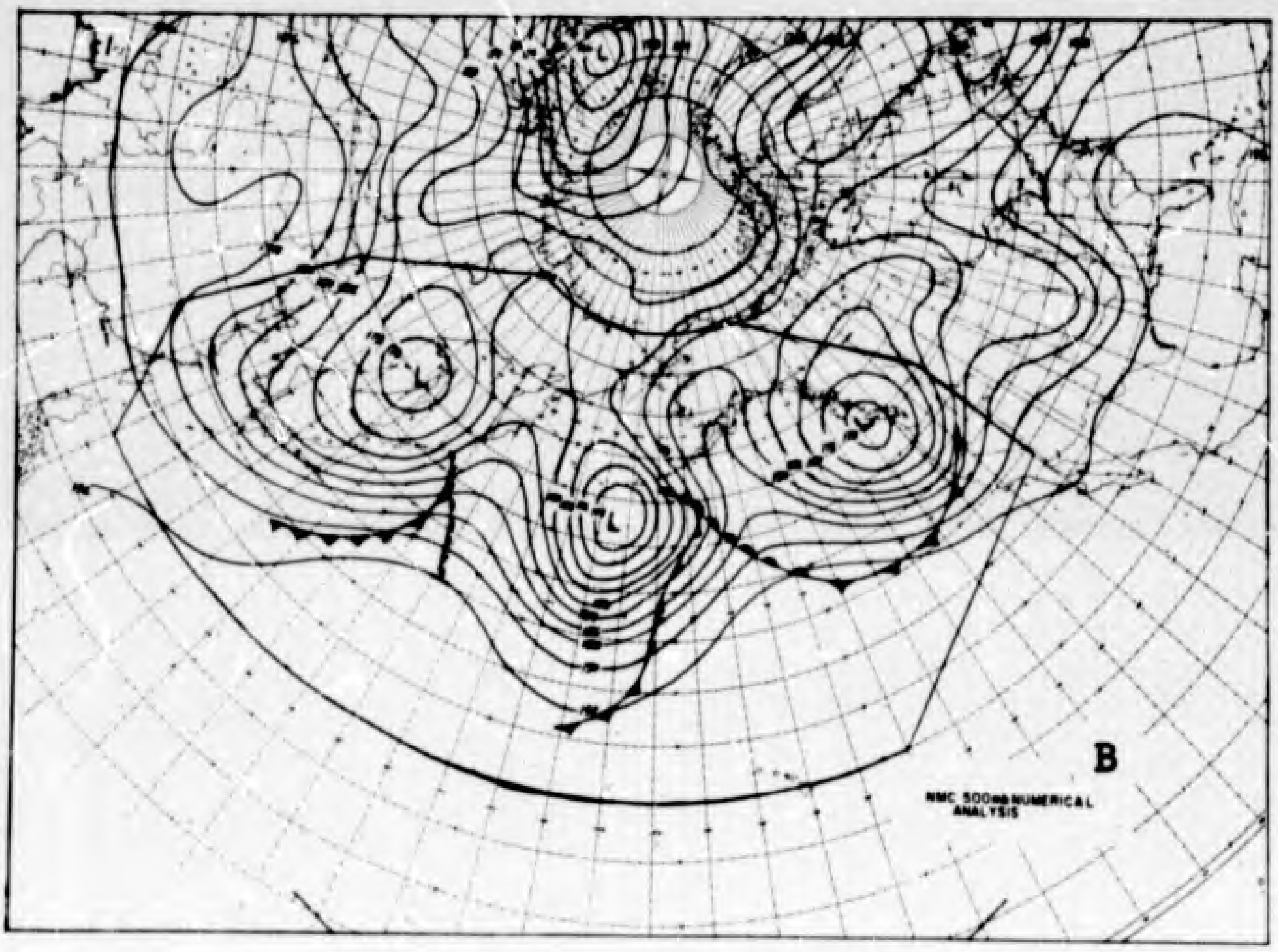


FIGURE 12.—(A) 500-mb. modified numerical analysis for 0000 GMT, May 21, 1960. (B) National Meteorological Center 500-mb. numerical analysis for 0000 GMT, May 21, 1960.

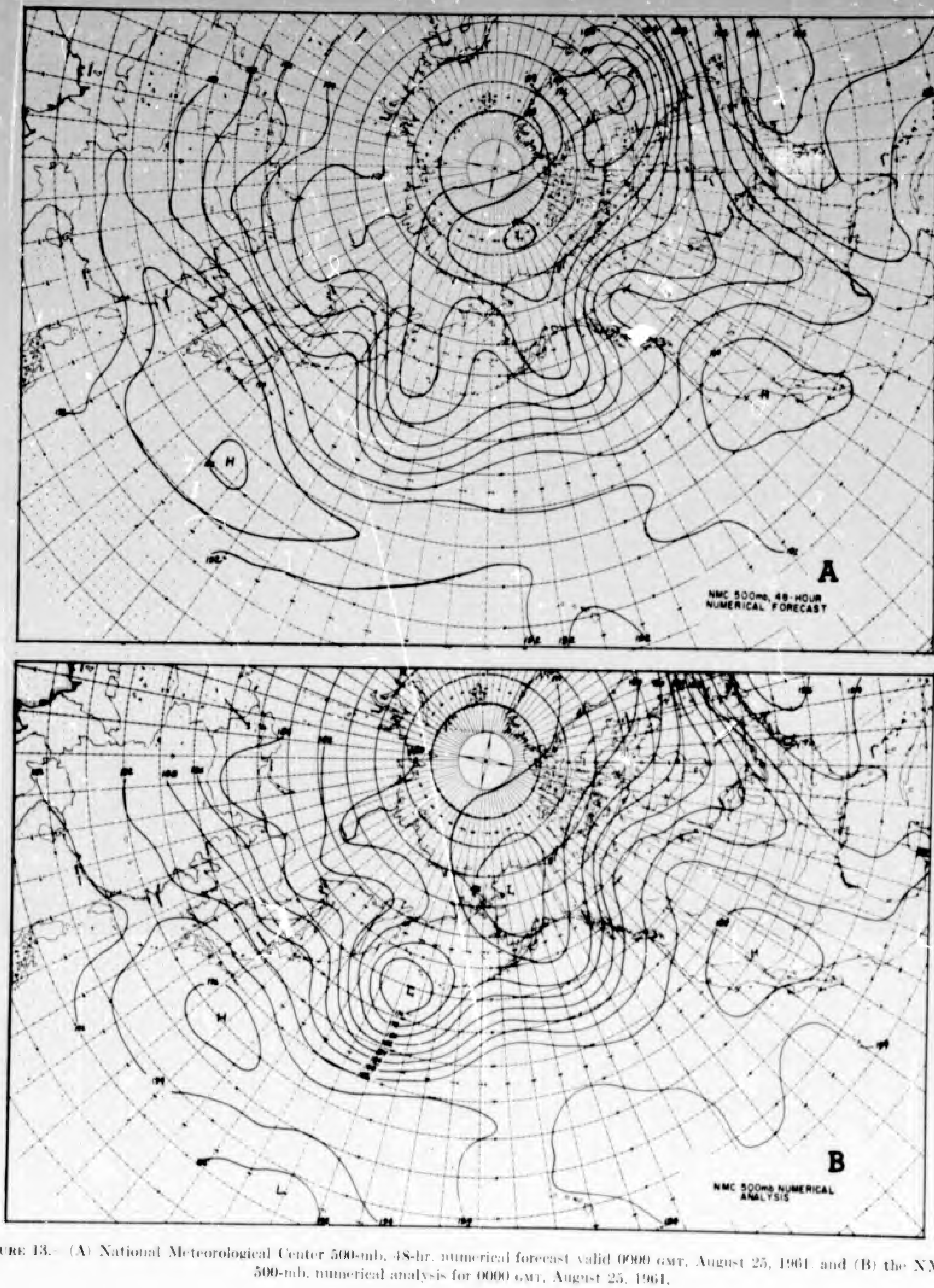


FIGURE 13.—(A) National Meteorological Center 500-mb. 48-hr. numerical forecast valid 0000 GMT, August 25, 1961, and (B) the NMC 500-mb. numerical analysis for 0000 GMT, August 25, 1961.

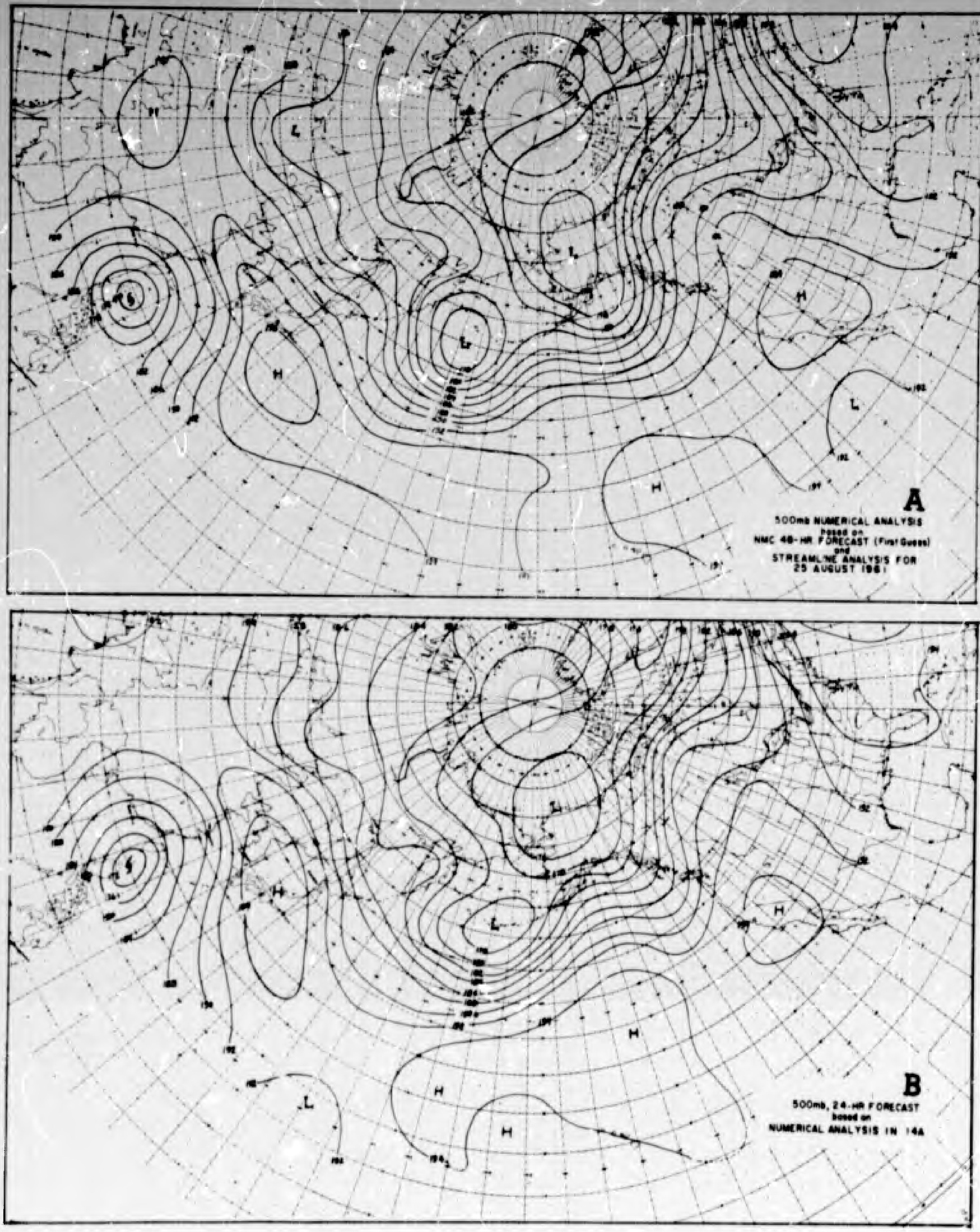


FIGURE 14.—(A) 500-mb. modified numerical analysis for 0000 GMT, August 25, 1961, and (B) a 500-mb., 24-hr. numerical forecast based on the analysis in (A).

8. CONCLUSIONS

From the above case studies and others not included, it seems plausible to conclude that a reasonable estimate of large-scale circulations for at least a middle level in the atmosphere can be deduced in most cases from TIROS cloud data. As one or more polar orbiting satellites are put into operation and new techniques for estimating cloud tops evolve, it may be speculated that kinematic analysis can be applied on a more nearly global scale, perhaps to more than one level. However, it is important to note that this approach is not intended to replace analyses based on conventional data. Over sparse data regions, particularly oceanic regions where upper-air observations are non-existent or few in space and time, this procedure can serve as an aid in estimating the large-scale trough and ridge patterns, these inferred patterns constituting by no means unique solutions.

This method, by the very nature of its application and the data employed, is subjective and has very definite limitations. Nevertheless, it does provide a means of obtaining at least a qualitative analysis over sparse data regions where none could be made otherwise. Reasonably accurate and useful subjective analyses can be made—skill in kinematic analysis assumed—providing there is a judicious application of physical and statistical climatology to serve as an analytical control. A working knowledge of the relationships between weather and the field of motion as well as the ability to interpret satellite observations of clouds in terms of types, elevations, and the effects of orography on them are also important prerequisites for performing this type of analysis.

Two possible applications of this technique which can serve as an aid in analyzing over sparse data regions are suggested:

a. A direct application of the streamlines and isotachs can be made to estimate the wind field at the analysis level.

b. Wind speeds and directions extracted from the streamline-isotach analysis can be introduced into a computer analysis program; hence a numerical re-analysis provides conventional height contour analyses at the desired level.

ACKNOWLEDGMENTS

The author is especially grateful to Lt. Col. James B. Jones, USAF for his helpful suggestions and the detailed nephanalysis of the May 1960 series and to Mr. David S. Johnson and Dr. S. Fritz, all of the National Weather Satellite Center, for their encouragement and valuable comments. The generous assistance of members of Detachment 51, 1210th Weather Squadron, Air Weather Service in the preparation of the charts and numerical analyses is also gratefully acknowledged.

REFERENCES

1. S. Fritz, "Cloudiness Associated with Large-Scale Synoptic Systems in Temperate Latitudes," *Proceedings of the International Meteorological Satellite Workshop,* NASA–U.S. Weather Bureau, Washington, D.C., Nov. 1961, pp. 45–65.
2. S. Fritz, "Satellite Cloud Pictures of a Cyclone over the Atlantic Ocean," *Quarterly Journal of the Royal Meteorological Society,* vol. 87, No. 373, July 1961, pp. 314–321.
3. S. Fritz and J. S. Winston, "Synoptic Use of Radiation Measurements from Satellite TIROS II," *Monthly Weather Review,* vol. 90, No. 1, Jan. 1962, pp. 1–9.
4. J. B. Jones, "A Western Atlantic Vortex Seen by TIROS I," *Monthly Weather Review,* vol. 89, No. 10, Oct. 1961, pp. 383–390.
5. J. Kuettner, "The Band Structure of the Atmosphere," *Tellus,* vol. 11, No. 3, Aug. 1959, pp. 267–294.
6. V. J. Oliver, "TIROS Fills the Void for World Weather Watch," *Weatherwise,* vol. 15, No. 4, Aug. 1962, pp. 160–162.
7. C. S. Ramage, "The Subtropical Cyclone," *Journal of Geophysical Research,* vol. 67, No. 4, Apr. 1962, pp. 1401–1411.
8. J. Sadler, "Utilization of Meteorological Satellite Cloud Data in Tropical Meteorology," Research Note, Air Force Cambridge Research Laboratory, 62–829, Aug. 1962.
9. N. Shaw, *Manual of Meteorology,* Vol. I, Cambridge University Press, 1926, 339 pp. (p. 268).
10. U.S. Weather Bureau, "Normal Weather Charts for the Northern Hemisphere," *Technical Paper* No. 21, Washington, October 1952, 74 pp.
11. H. Wexler, "TIROS Experiment Results," *Space Science Reviews,* vol. 1, 1962, pp. 7–27.
12. C. J. Wiederanders, "Analyses of Monthly Mean Resultant Winds for Standard Pressure Levels over the Pacific," *Science Report* No. 3, Contract No. AF 19(604)–7229, University of Hawaii, Mar. 1961.
13. J. S. Winston, "Satellite Picture of a Cut-Off Cyclone over the Eastern Pacific," *Monthly Weather Review,* vol. 88, Nos. 9–12, Sept.–Dec. 1960, pp. 295–314.

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APPENDIX C

DEDUCTIONS FROM RECENT STUDIES OF CLOUD LINE ORIENTATIONS AND CONCURRENT WIND DIRECTIONS

The relationships between wind direction (let alone speed) and such cloud patterns as lines, streets, bands, etc., are, at best, complex. Varied indications showing cloud orientations both parallel and perpendicular to the wind flow, as well as parallel to the wind shear vector, have been obtained from studies of satellite cloud pictures. It is probable that considerable time, study, and effort remain before anything approaching unambiguous results is at hand.

Some light would appear to have been shed on the basic sources of these difficulties by recent studies[68], and an understanding and utilization of the principles of these findings may assist in the deduction of wind direction from cloud patterns in those cases where the nature of the cloud pattern being examined is available from the information in the picture. In any event, these findings give a better idea than may previously have been available on the nature and extent of the ambiguities inherent in wind direction deductions using cloud patterns.

When there is a single shear between a cloud layer moving fairly uniformly and the ground or ocean surface, the parallel mode* develops by a simple superposition of cloud rolls parallel to the wind and individual clouds leaning with the shear. This mode of formation is illustrated in Figure C-1 and an example is given in Figure C-2. When there is wind-turning within the cloud layer, the individual clouds lean across the rows, which may then be several clouds wide. A case of this parallel mode with rows several clouds wide is illustrated in Figure C-3, and the mode of formation in Figure C-4.

A marked shearing imposed aloft upon the convective layer brings in the cross-wind mode, oriented with the upper shear. It may be superposed on the parallel mode to make a checkerboard, or in extreme instances it may appear alone, so that the only cloud rows seen are at a high angle to the wind. Two striking examples are shown in Figure C-5. In such cases, cumuli will line up in the directions of both the low-level wind and the wind above the shear layer;

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* Cloud lines or streets parallel to the wind.

the anvils line up along the shear vector between the low-level wind and the wind at anvil level. The observed 40 to 50 mile spacing of the cross-wind mode may be coincidental, or it may provide a clue to the dynamics of this mode that we do not yet know how to interpret. The factors that govern the relative degree of development of the two modes (parallel versus cross-wind) are still unspecified.

A very significant problem from the viewpoint of the satellite meteorologist is that available camera resolution will usually prevent seeing the individual, single cloud rows in the parallel mode. Accordingly, when attempting to interpret the winds associated with those clouds that do appear arranged in rows, there is often little or no basis for determining whether they represent the cross-wind mode or the parallel mode with rows several clouds wide.

In additio to the problems that exist in correctly interpreting the parallel and cross-wind modes associated with such "cloud streets", there is also the problem of differentiating between them and lines of cumuliform clouds oriented more or less perpendicular to the wind flow. These cloud lines appear to be related to the billow clouds frequently seen from the ground (formed along inversions) but are, of course, of considerably greater scale when seen in the satellite pictures.

Fig

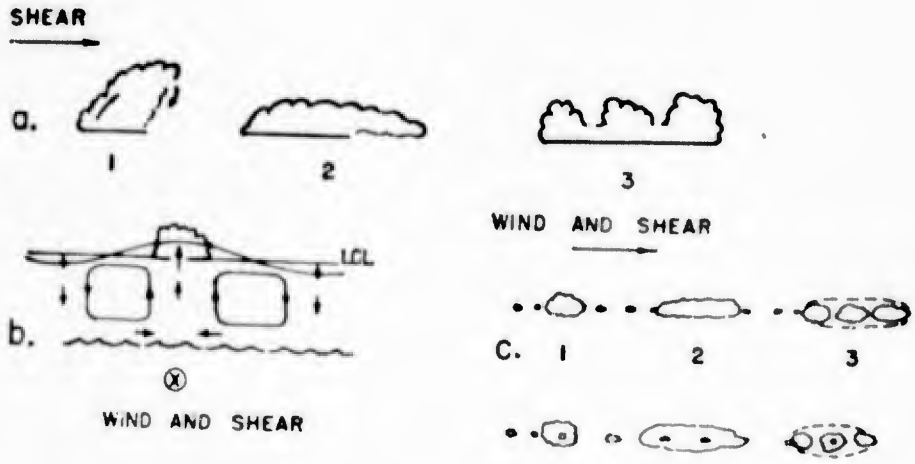

Fig. C-1 Schematic illustration of the formation of rows of cumuli when the low-level wind and the shear in the lower cloud layer lie in the same plane. a. The effect of shear in three stages: (1) Little growing cloud tilts downshear, and (2) lies down downshear as updraft dies; (3) new little cloud grows from the prostrate body. b. The effect of Avsec rolls, wind, and shear at right angles to plane of diagram (blowing into the paper). The wavy line denotes the top of the mixed layer, raised in zones where the roll motion is convergent and upward, depressed where the roll motion is divergent and downward. Cloudlets break out where the mixed layer reaches condensation level-- that is, at roll crests. c. Combination of the direct shear effect in a and the Avsec rolls in b produces cumulus rows parallel to the flow, which elongate downshear. (From Reference 68)

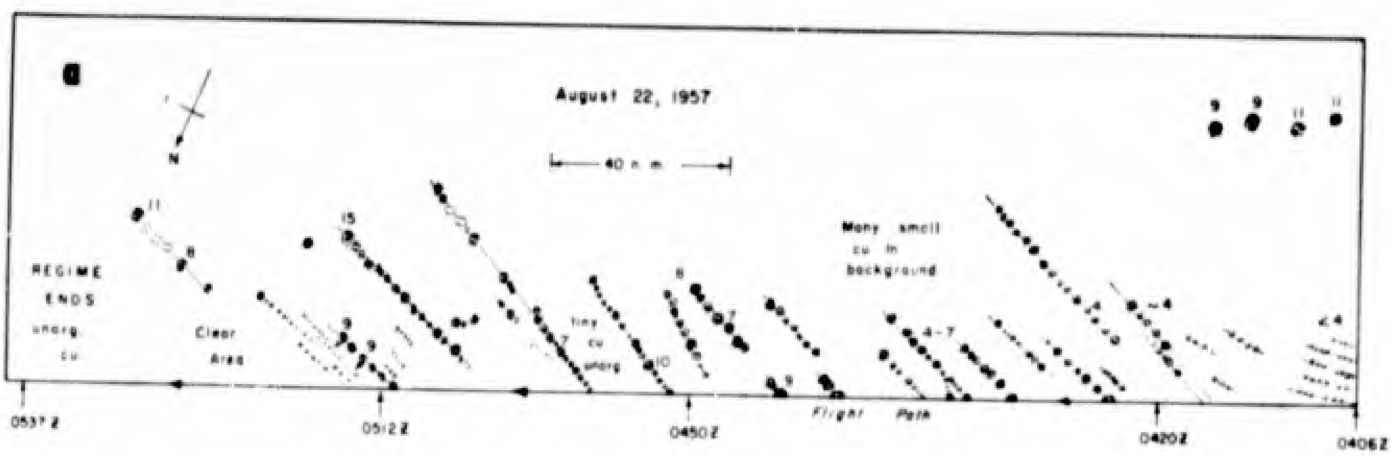

Fig. C-2 The simplest case of the parallel mode, with cloud rows one cloud wide, occurring when trade wind and vertical shear are in the same plane.... Cloud heights are in thousands of feet; when the height of an individual cloud is given, this cloud is generally the highest in its row. The surface winds were from the southeast, with no wind turning with height. (From Reference 68)

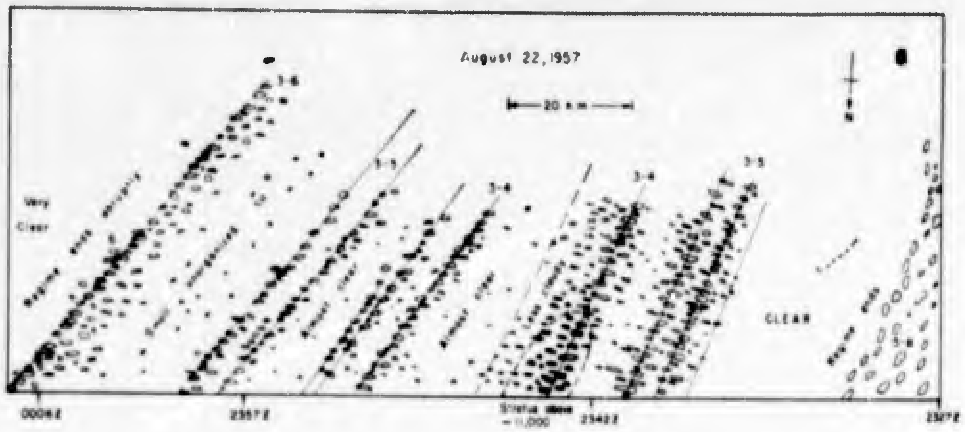

Fig. C-3 Parallel mode with rows several clouds wide, occurring when the trade wind and the vertical shear in the cloud layer are at a high angle to each other... Not all the clouds photographed were included. The length and spacing of the rows are to scale. The height ranges are in thousands of feet. The shaded region denotes a patch of stratus above the cloud row. The surface wind was from the northeast at 0000 GMT. (From Reference 68)

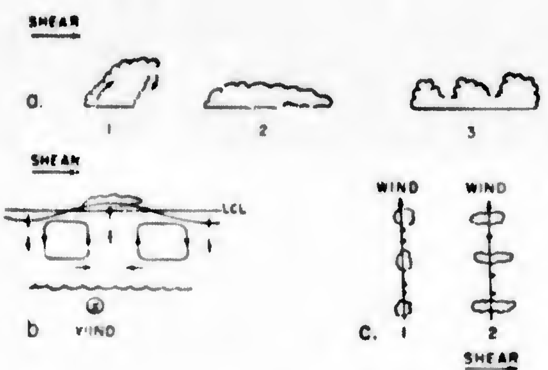

Fig. C-4 Schematic illustration of the formation of rows of cumuli when the low-level wind and the shear in the lower cloud layer are at right angles to each other. a. The effect of the shear elongates the cumuli downshear, as shown in Fig. C-1a. b. Avsec rolls lined parallel to the wind (which blows directly into the diagram) but at right angles to the shear (which points from left to right in the plane of the diagram). Cloud rows develop along the direction of the wind, as suggested in Fig. C-1b but the individual clouds are elongated normal to the rows. c. Combination of a and b showing the clouds stretched downshear normal to the Avsec rolls. The clouds are most likely to break out along the roll crests, but there is some spreading into the interstices. (From Reference 68)

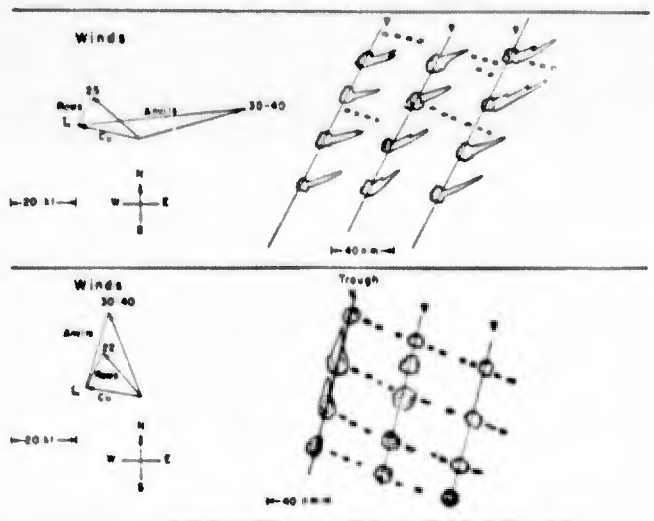

Fig. C-5 A schematic summary of cloud organization in the presence of cross-wind shear. Winds (in knots) are shown at left. L, low-level wind; arrows marked 25 and 22, respectively (for thousands of feet), winds above the shear layer; arrow marked 30-40, the mean wind for the 30,000- to 40,000-foot layer, or anvil region Note that cumuli (cu) line up in the direction of the low-level wind; the cross-wind rows line up along the shear vector between the low-level wind and the wind above the shear layer; anvils line up along the shear vector between the low-level wind and the wind at anvil level. (From Reference 68)

LOCAL TROPICAL ASPECTS

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APPENDIX D

LOCAL ASPECTS OF TROPICAL SATELLITE ANALYSIS

As discussed in Chapter 11, while tropical meteorological phenomena (in a general sense) are not restricted to any one region, it is necessary to take into account the region under consideration for optimum results when analyzing or forecasting any specific tropical phenomena[72].

While many of the studies of tropical storms listed in the References can be considered as contributing to the knowledge of the areas of the western North Atlantic, Carribean, and Gulf of Mexico, and to that of the western North Pacific, only two tropical areas appear so far to have been at all extensively studied from a truly regional viewpoint. They are the eastern North Pacific[96, 97*], and the areas of West Africa and the eastern North Atlantic.[53,73] Perhaps slightly more effort has to date been placed on the summer season of the eastern North Pacific.

The following discussions of conditions as observed in these regions using satellite data are included to provide the analyst further examples of types of tropical phenomena he is likely to see in these areas. It is probable that similar phenomena will also be seen in other, but climatologically analogous, tropical regions.

D.1 THE EASTERN NORTH PACIFIC IN SUMMER

Based principally on TIROS data, there is now little doubt that convergence lines or zones of heavy cloudiness (Figs. 11-8a, D-2) represent one of the dominant features of the summer low-level monsoonal circulation of the eastern Pacific. The following remarks concerning observed convergence zones may also apply in general to other tropical oceanic areas dominated by a monsoon trough and in particular to the eastern Atlantic, which has a very similar summer monsoonal circulation regime of the low atmosphere and a similar sea-surface isotherm distribution on either side of the monsoonal trough[96].

* See also J. Applied Meteorology, 3 (4), pp. 347-366, August 1964.

D. 1. 1. The Monsoonal Convergence Zone

The principal convergence zone and its related major cloud band is not located along the trough but is some 2 to 3 degrees south of the trough line (Figs. 11-8). This convergence takes place between the westerlies on the south side of the trough and the flow from the southern hemisphere which turns anticyclonically from southeast through south to southwest. The northern edge of this convergence zone is usually rather sharp as opposed to the "feathered" or ragged appearance of the southern portion[96].

There is a secondary line of convergence located to the north of the trough line (Fig. 11-8a) which is also displaced from the wind-shift line. This zone is frequently absent and when present is much less intense than the southern convergence zone. This is as would be expected due to the stability and dryness of the trade wind zone as compared to the instability and raininess of the westerly component monsoon air[96].

TIROS data have shown the area between the convergence lines to be one of minimum cloudiness (Fig. 11-8a). This minimum cloud area is more or less centered about the wind-shift line which is also the minimum pressure or trough line. The trough is, in fact, likely to be clear or to contain only scattered clouds except for concentrated cloudiness associated with the tropical cyclones traveling along the trough[96].

It is possible that the TIROS data so far studied for the Eastern Pacific may represent "active" periods with "activity" being a measure of the westward extension of the trough and a procession of westward traveling tropical cyclones, of various intensities, along the trough. Frequency of the active periods undoubtedly varies from year to year, and even within seasons, similar to that which has been observed in the Western Pacific; however, TIROS data do show that once an active period is initiated it can persist for weeks. During this period we would expect, and TIROS does confirm, that the convergence zone to the south would be persistent and would have a large longitudinal westward extension with the trough. TIROS data show this convergence zone more or less "anchored" near 10N and extending westward to beyond 160W. If all the cyclones are tracking along the trough we would also expect (and again TIROS does confirm) the northern convergence zone to be more apparent. Where a hurricane is traveling north of the trough, the trades are disrupted and the northern convergence zone is displaced far to the north (Fig. D-1) by the hurricane circulation[96].

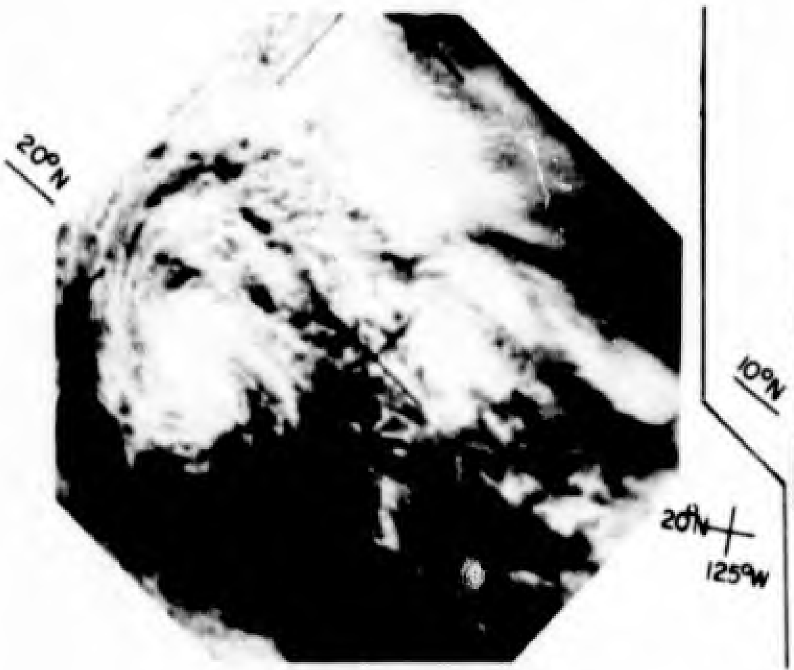

Fig. D-1 Eastern Pacific Convergence Zone Displaced to North

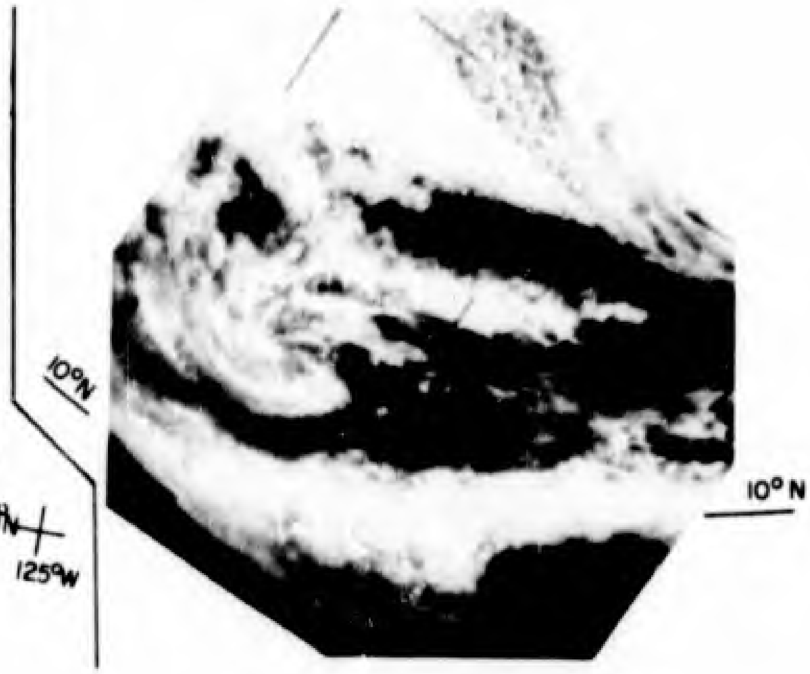

Fig. D-2 Little Change of Eastern Pacific Convergence Line with Weak Cyclone

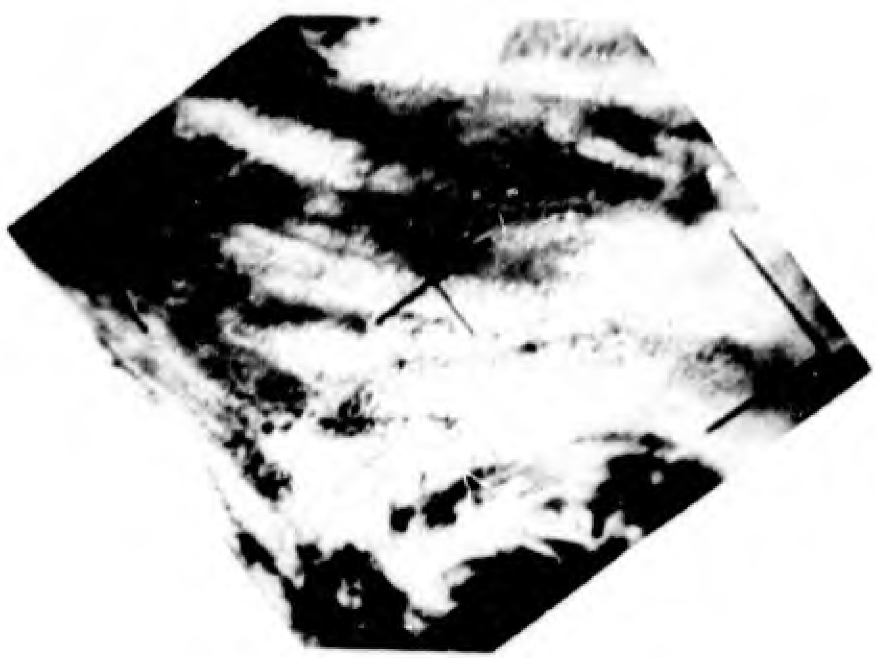

Fig. D-3 Tropical Eastern Pacific, Cold Air Stratus and Stratocumulus

There is a tendency for the northern convergence zone to return southward to a normal position just north of the trough line as the hurricane moves off to the west[96].

The orientation and intensity of the convergence lines, on a daily or synoptic scale, responds to the passage of tropical cyclones. The more intense the cyclone the more influence it exerts on the alignment of convergence lines within its vicinity (Fig. D-1). If cyclones traveling along the trough line are relatively weak, the convergence lines show little realignment response during their passage (Fig. D-2)[96].

D. 1. 2 Tropical Storms

This monsoonal trough appears to be the breeding zone for eastern North Pacific tropical storms. Studies of these storms, based on TIROS data, indicate[97,*]:

1. The eastern North Pacific ranks second to the western North Pacific in the annual frequency of tropical cyclones of tropical storm and hurricane intensity.

2. A comparison of many TIROS photographs of western Pacific typhoons, of known intensity and size, with photographs of eastern Pacific hurricanes reveals that (a) eastern Pacific hurricanes are small in size (Fig. D-1) and, (b) the maximum intensities of those viewed to date were near 100 kt.

3. The small size and only moderate intensities are attributed, in part, to the restricted area of warm water over which they form and to the relatively close proximity of very cold water on either side of the formation area.

4. The cyclones are able to maintain a rather vigorous intensity for long distances into and along a cold environment. The resultant component of the strong winds of the outer-storm circulation in confluence with the lighter northeast winds of the cold air mass is such as to prevent cold air entering the storm center along a direct trajectory. Mixing is confined to the outer edges of the storm and even the mixed air has a long trajectory over warmer waters before entering the storm circulation, usually in the southern sector.

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* Also see footnote on p. 365.

As the tropical storms advance into the region of strong gradients of surface air and water temperatures, the storm's outer circulation acts as a barrier in preventing cold air from entering directly into the inner storm circulation. The differences in the air masses are portrayed in the cloud structure (Fig. D-3). The cold air is characterized by the typical stratus and stratocumulus underneath the trade wind inversion and is readily distinguished from the thicker convective clouds within and on the periphery of the storm circulation. In addition, a clear or minimum-cloud zone separates the cloud bands from the stratified clouds to the north of the storm circulation. This self-contained "shield" undoubtedly accounts for many of the storms being able to penetrate thousands of miles into and along the edge of this cold environment*. It is also likely that the storm circulation modifies the pattern of the sea-surface isotherms in a similar manner but to a much lesser degree.

5. The dominant dissipating influence on tropical storms and hurricanes tracking west and west-northwest out of the principal development area of the eastern Pacific is extreme vertical wind shear produced by the tropical upper-tropospheric westerlies. Sufficient conventional meteorological and oceanographical data are not available on a daily basis to separate the relative influences of the cold environment and the vertical shear in the dissipation of those storms tracking northwest through north.

6. The minimum intensity at which a developing depression first exhibits a good recognizable vortex cloud pattern undoubtedly varies from cyclone to cyclone. Evidence to date leads to an estimate of about 25 kt. The reverse relationship is not valid for a decaying cyclone. The vortex cloud pattern is very persistent and is apparent for many days in a decaying cyclone with very weak circulation (Fig. 11-48b).

7. TIROS data have revealed that many tropical cyclones travel westward into the central Pacific at latitudes below 15N. The data have not, as yet, had sufficient continuity in this region to determine the cyclone frequency and tracks, nor the implied circulations through which the vortices must travel.

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* A cold, dry air intrusion, in the case of tropical storm Alma, 1962, off the east coast of the United States, was used to successfully forecast storm weakening (see Jones, J. B., and L. M. Mace, "TIROS Meteorological Operations," <u>Astronautics and Aerospace Engineering</u>, <u>1</u> (3), pp. 32-36).

D.2 WEST AFRICA AND THE EASTERN NORTH ATLANTIC

Disturbances which develop over west Africa appear to be related to subsequent weather systems and conditions over much of the tropical portion of the North Atlantic Ocean.[73]

D.2.1 The Southwest Monsoon

TIROS observations were used to follow the northward progress of the moist West African Southwest Monsoon. In February, very little cloudiness could be found inland from the coast; heavy cumuliform cloudiness which relates to the Intertropical Convergence Zone (ITC) paralleled the equator at about 3°N. During the first half of April, the advance of the shallow moist layer was clearly marked by streets of small cumuliform cloud oriented southwest-northeast (Fig. D-4). Conventional wind observations at altitudes below the 3,000 foot level showed that these bands were parallel to the wind flow from the surface to the 3,000 foot level; apparently the depth of the moist air was insufficient to permit convective penetration into the easterlies which existed above 3,000 feet.[73] (Other studies[37] have also shown that, in the tropical Atlantic, the shear vector at low levels often parallels the wind and the cloud lines are related (essentially parallel) to the wind direction). By mid-April, the ITC cumuliform cloudiness had moved slightly northward to an average position near the Nigerian and Ghanian coast at 4°N.[73]

By the first week in July the cloud pattern over the W. African continental area had reached an average position near 16°N. The cloud bands visible in the TIROS photographs had changed their apparent major orientation from the southwest-northeast pattern visible in April (Fig. D-4) to one which suggested a major east-west banding (Fig. D-5) superimposed over a lesser southwest-northeast pattern. This suggests that the depth of the moist layer, which had now reached about 6500 feet over much of the area, permitted convective penetration of clouds into the upper level easterly flow. The ITC clouds had not moved north of the coast of Ghana or Nigeria, but there were frequent northward advances of these heavy bands over the coastal Atlantic areas[73] (Fig. D-5).

Fig. D-4 Shallow Moist Layer over West Africa; April

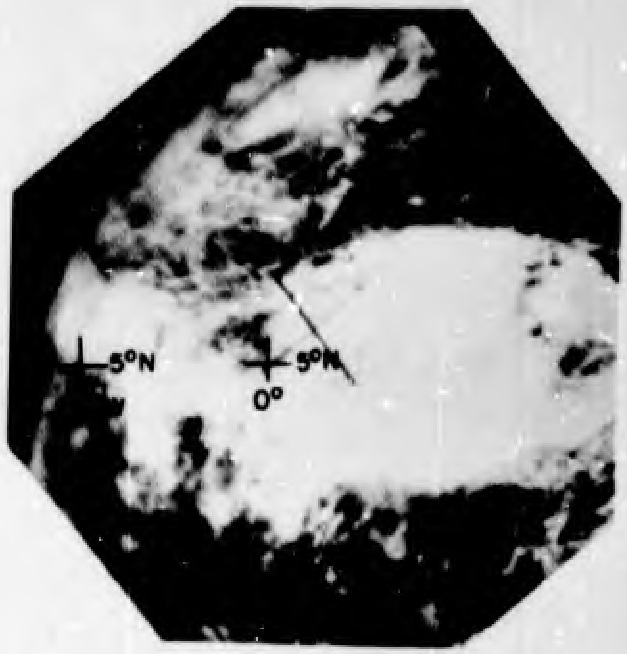

Fig. D-5 Intertropical Convergence Cloud Band over West Africa; July

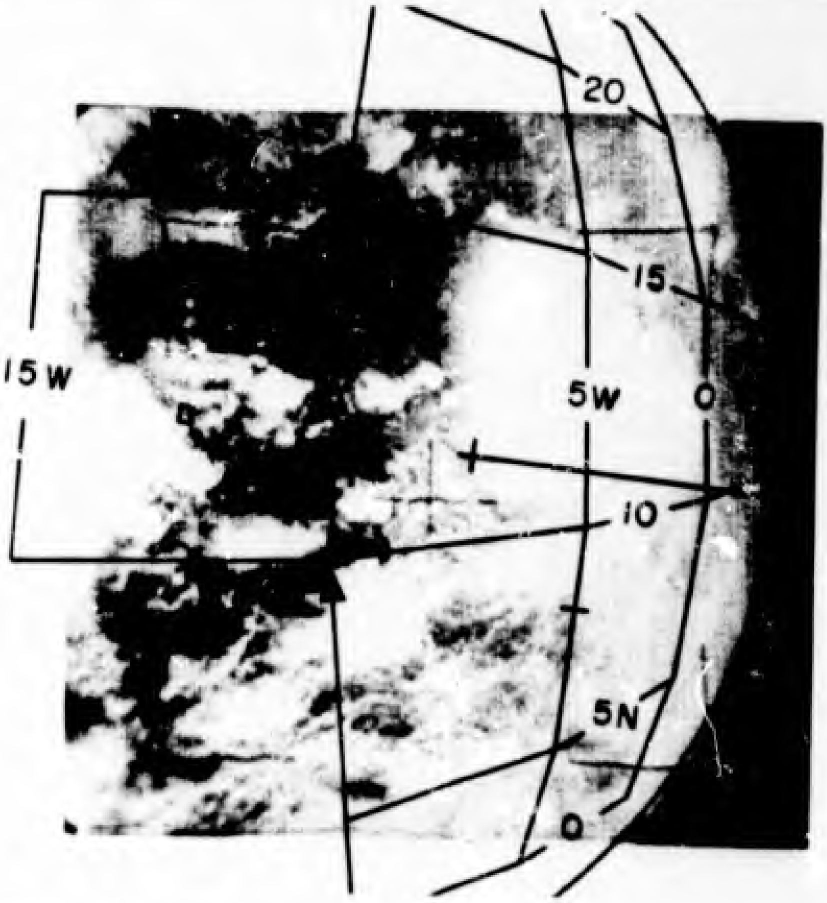

Fig. D-6 Cloudiness along Convergence Zone and Associated with Cyclonic Disturbance over West Africa; September

In September of one year the heavy cumuliform, cellular cloudiness of the ITC made frequent advances to about $8^{\circ}N$ (Fig. D-6). Conventional wind observations during this period indicate a cyclonic turning of the winds in the 8-14 thousand foot layer. This same pattern was noted on observations for a subsequent September, but the advances of the ITC cloud band were not as frequent or as far north. There were a number of cases in which these West African disturbances occurred concurrently with a zonal band of strong 12-18 thousand foot winds appearing north of the area of slightly lower cyclonic curvature. Therefore, the disturbances appear to be associated with an area of cyclonic curvature in the streamline field and cyclonic horizontal shear in the speed field.[73]

D. 2.2 African Disturbances

TIROS data have also been used to investigate the structure of cloud systems for disturbances over Africa which are assumed to be analogous to the line squall in other literature, but do not seem to possess the previously established characteristics of squall line cloud systems.[53]

The preliminary model which has evolved from these analyses seems to have the following characteristics as seen from TIROS:[53]

(1) A mass of middle cloudiness precedes the center of circulation or wind veering axis by about 200 miles and continues unbroken up to this circulation center or wind veering axis (Fig. D-6; 12N, 5W).

(2) A defined suppression of all but very low level cumulus occurs to the rear of the circulation center or wind veering axis (Fig. D-6, 5E).

(3) Cumulonimbus activity will occur along convergence axes usually to the southwest and southeast of the disturbance cloud mass (Fig. D-6; along 10N). In addition to these TIROS-observed characteristics, the following surface and upper air features may appear in conventional analyses[53]:

(1) Most of these disturbances will not exhibit any defined surface circulation.

(2) Those disturbances which do have a defined surface circulation are probably under an area of upper level divergence and are thus suspect for possible tropical storm development.

This preliminary model of a vortical rather than linear cloud distribution related to disturbances over Africa seems to upgrade their status in the Cape Verde area tropical storm evolution picture. These related upstream development conditions may be important to Atlantic hurricane formation.[53]

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APPENDIX E

SUGGESTIONS FOR ADDITIONAL READING

While it is hoped that, within the limits of the existing state of the art, this report will be self-sufficient as regards providing guidance to the analyst or forecaster in the operational utilization of meteorological satellite data, there may be those who would care to look further into some of the topics discussed. While applicable specific references have been cited throughout the main portion of the report, the following list of selected references for further reading may be helpful to those interested in a broader general knowledge of the subject.

GENERAL REFERENCES

Final Report on the TIROS I Meteorological Satellite System, Technical Report R-131, National Aeronautics and Space Administration, 1962; see Part II, Chapters 8-18, papers by staff members of the Meteorological Satellite Laboratory, U. S. Weather Bureau.

Proceedings of the International Meteorological Satellite Workshop, NASA-USWB, 1961; published by the U. S. Government Printing Office.

Wexler, H., and J. E. Caskey, Jr. (Editors), 1963: Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam (U. S. Distributor: John Wiley and Sons, Inc., New York).

"Weather Satellite Systems," Astronautics and Aerospace Engineering, April 1963 issue; see especially:

Jones, J. B., and L. M. Mace; "TIROS Meteorological Operations," pp. 32-36.

Fritz, S.; "Research with Satellite Cloud Pictures," pp. 70-74.

Nordberg, W.; "Research with TIROS Radiation Measurements," pp. 76-83.

Singer, S. F., and R. W. Popham; "Non-meteorological Observations from Weather Satellites," pp. 89-92.

Kondrat'yev, K. Ya., 1963: Meteorological Satellites, NASA Technical Translation F-177, published May 1964, available from Office of Technical Services, Department of Commerce, Washington, D. C.

ORBITAL FACTORS AND COVERAGE

Widger, W. K., Jr., and C. P. Wood, 1961: "An Explanation of the Limitations to the Coverage Provided by TIROS," Weatherwise, 14 (6), pp. 230-237.

LOCATION AND RECTIFICATION OF APT DATA

Goldshlak, L., 1963: APT User's Guide, Scientific Report No. 1, Contract No. AF 19(628)-2471, Allied Research Associates, Inc.

CLOUD IDENTIFICATION

Conover, J. H., 1962: Cloud Interpretation from Satellite Altitudes, AFCRL Research Note 81, (also summarized in Rocket and Satellite Meteorology, pp. 389-392).

Conover, J. H., 1963: Supplement 1 to Cloud Interpretation from Satellite Altitudes, Supplement 1 to AFCRL Research Note 81.

Erickson, C. O., and L. F. Hubert, 1961: Icentification of Cloudforms from TIROS I Pictures, Meteorological Satellite Laboratory Report No. 7, U. S. Weather Bureau.

SPARSE DATA AREA ANALYSIS

Miller, F. R., 1963: "An Application of TIROS Cloud Observations in Sparse Data Regions," Monthly Weather Review, 91 (9), pp. 433-451 (Included as Appendix B to this report).

SEVERE STORMS

Whitney, L. F., Jr., 1963: "Severe Storm Clouds as Seen from TIROS," Journal of Applied Meteorology, 2 (4), pp. 501-507.

OROGRAPHIC CLOUDS

Conover, J. H., 1964: "The Identification and Significance of Orographically Induced Clouds Observed by TIROS Satellites," Journal of Applied Meteorology, 3 (3), pp. 226-234.

TROPICAL METEOROLOGY

Sadler, J. C., 1963: "Utilization of Meteorological Satellite Cloud Data in Tropical Meteorology", Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, pp. 333-356, (also published as AFCRL Research Note, August 1962).

SYNOPTIC USE OF INFRARED DATA

Rao, P. K., and J. S. Winston, 1963: "An Investigation of Some Synoptic Capabilities of Atmospheric 'Window' Measurements from Satellite TIROS II," Journal of Applied Meteorology, 2 (1), pp. 12-23.

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APPENDIX F

SELECTED BIBLIOGRAPHY ON METEOROLOGICAL SATELLITES, THEIR OPERATION, AND ACQUISITION AND PROCESSING OF THEIR DATA

This report has attempted to provide, as fully as the current state of the art makes possible, information required by Air Weather Service forecasters when using, interpreting, and applying meteorological satellite data. At the same time, the report has attempted to avoid discussion of topics, regardless of how well related or how interesting, that are not required by the forecaster.

It is recognized that many forecasters may have either a personal or a professional interest in learning more about meteorological satellites, how their equipment works, operational procedures used in acquiring and initially processing the satellite data, anticipated future systems and their capabilities, and similar topics. Since it did not seem desirable to increase the size of this report to the extent necessary if such information were to be included, as an alternative this appendix provides a list of selected and reasonably available references containing these types of information.

NASA-USWB, 1961: Proceedings of the International Meteorological Satellite Workshop, U. S. Government Printing Office.

Staffs, Goodard Space Flight Center and U. S. Weather Bureau, 1962: Final Report on the TIROS I Meteorological Satellite System, NASA Technical Report R-131.

National Weather Satellite Center, 1963: Reduction and Use of Data Obtained by TIROS Meteorological Satellites, Technical Note No. 49, World Meteorological Organization.

Stampfl, R. A., 1962: The Nimbus Spacecraft and Its Communication System as of September 1961, NASA Technical Note D-1422.

Stampfl, R. A., and H. Press, 1962: "Nimbus Spacecraft System," Aerospace Engineering, 21 (7), pp. 16-28 (July issue).

Tepper, M., S. F. Singer, and J. Newbauer (Editors), 1963: "Weather Satellite Systems," Astronautics and Aerospace Engineering, 1 (3), pp. 22-96 (April issue).

For a more comprehensive bibliography on these and related matters, including research conducted with meteorological satellite data, the reader is referred to:

Kiss, E., 1963: Bibliography on Meteorological Satellites (1952-1962), U. S. Weather Bureau, available from Superintendent of Documents, U. S. Government Printing Office.

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