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THE RELATIONSHIP BETWEEN MARITIME PRECIPITATIO RADAR ECHOES AND CLOUD COVER VIEWED BY SATELLITES IN POLAR ORBITS

By: ROY H BLACKMER, JR. SIDNEY M SEREBRENY

Prepared for:

OFFICER-IN-CHARGE, PROJECT FAMOS
U.S. FLEET WEATHER CENTRAL
SUITLAND, MARYLAND — CONTRACT N62306-1642

AND

CHIEF, APPLICATIONS GROUP
NATIONAL ENVIRONMENTAL SATELLITE CENTER
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SRI Projects 5412 and 5562

Approved: M. G. H. LIGDA, MANAGER
AEROPHYSICS LABORATORY

D. R SCHEUCH, EXECUTIVE DIRECTOR
ELECTRONICS AND RADIO SCIENCES

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ABSTRACT

Analyses of concurrent radar data and TIROS IX cloud photographs were made to develop techniques for determining areas of precipitation and severe weather within a given satellite observed cloud situation. During the four-month period studied (14 February to 15 June 1965), there were a number of occasions when frontal bands or cyclone centers were within range of one or more of the ten radar sites at the time of satellite passage. Examples of the precipitation distribution associat with various synoptic patterns are presented with discussions of pertinent features of the attendant cloud cover. From these examples a mode of the probable distribution of precipitation within and around a typic maritime cyclone was constructed. The report also discusses situations in which there is widespread cloud cover but little or no precipitation

CONTENTS

ILLUSTRATIONS*

*Bound separately as Vol. II.

TABLES

I INTRODUCTION

Since 1960 there have been rapid increases in the quantity and quality of cloud data available to the meteorological community from cameras aboard earth-orbiting satellites. TIROS I provided intermittent coverage depending on its attitude. More recent satellites of the "cartwheel" type provide continuous coverage in overlapping strips, and at the present time a number of such satellites are in operation, so that there is complete coverage more frequently than once a day. In addition to improvements in photographic coverage and frequency of such coverage, there have also been improvements in making the photographs available to various users. The APT systems make it possible for any interested party to receive detailed photographs of the cloud cover in his area directly from the satellite. Eventually, equipment for so doing will be in operation at many places where local forecasts are made, just as radar and radiosondes are used today to gather information beyond an observer's limited field of view. Such satellite data should prove to be valuable to forecasters in sparse data areas such as the vast ocean areas of the globe. In these ocean areas there are many ships aboard which meteorological personnel prepare forecasts with a very limited amount of data. The receipt several times daily of a photograph of the cloud cover over many thousands of square miles around the ship would, <u>if such photographs were properly interpreted</u>, provide a wealth of information that would greatly aid the forecaster. The problem of interpreting the cloud photographs in terms of other parameters such as pressure systems varies in complexity. At times the cloud configuration unmistakably indicates the presence of frontal bands or well developed low-pressure areas. At other times the clouds do not show any specific pattern that would aid in locating synoptic features. In either case there is the problem of determining whether or not there may be any precipitation associated with various portions of the cloud cover. It is the purpose of this study to determine the relationships between cloud photographs obtained from a polar orbiting meteorological satellite and precipitation echoes observed by radar. The research is intended to develop techniques for determining areas of precipitation within a given satellite-observed cloud situation.

A number of studies of concurrent radar and satellite data have been conducted by various groups. At Stanford Research Institute, analyses were made of radar data collected by a widespread network of radar stations during the period when TIROS I was taking useful photographs. Some of the problems of working with data from this satellite were the varying angle of view at which photographs were taken, the lack of daily coverage over a given location, and difficulties in determining the geographical location of the photographed cloud cover. In spite of these difficulties a number of cases were studied. The results of these studies as reported by Nagle and Blackmer[1]* were that "no characteristics are found that will allow a specific determination to be made of clouds that are of a precipitating nature, although the limitations of the TIROS I data may have precluded such a determination. However, on a gross scale, the brightest clouds are found to have been associated with areas of precipitation."

Other studies such as those by Nagle and Serebreny,[2] Whitney,[3] Blackmer,[4] Fujita et al.,[5] and Hiser and Senn[6] have compared satellite-viewed cloud cover and concurrent radar data for various types of situations. The data used were from TIROS satellites similar to TIROS I; hence the investigators were still hampered by the lack of recurrent coverage of a given area at low nadir angles.

The present study was conducted using cloud photographs from TIROS IX. This was a polar orbiting satellite--the first of the cartwheel type. Because of the method of stabilization and the orientation and operation of the cameras the satellite sub point was nearly always located within the area photographed. Thus, a portion of each photograph contained a plan view of cloud cover. Toward the horizon the

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*References are listed at the end of the text.

angle of view to the clouds naturally increased, becoming tangent at the horizon. Due to the orbital characteristics the same area of the earth's surface was photographed each day at approximately the same time. The area in which we were interested was the eastern Pacific Ocean and the west coast of the United States. Figure 1 includes the area of interest and shows the location and approximate area of coverage of the radar sites from which radar data were collected between mid-February and the end of June 1965. These radar data, by virtue of the radar sets employed in the data-collection program, show, with but few exceptions, regions of precipitation embedded within the clouds. The relatively few exceptions, as described in Appendix C, are situations wherein there is cloud (from which no precipitation is falling) that is dense enough to return an echo to the radar.

The radar data and TIROS IX data were analyzed to find answers to a number of specific questions. The specific tasks that were to be performed were spelled out in the contractual statement of work as follows:

(1) The patterns of cloud elements and precipitation echoes will be compared to assess:

  (a) Under what circumstances the rainfall pattern very closely approximates the satellite viewed cloud pattern.

  (b) Whether the lack of a patterned association is random, or limited to particular synoptic situations or conditions of cloud cover.

  (c) What scale of radar detail shows in cloud patterns.

  (d) Whether transitions of precipitation echo type and cloud pattern coincide.

(2) The life history of weather existing systems will be studied using satellite and synoptic data and, as

they traverse the radar network, radar data, to determine:

(a) How far in advance of approaching storm systems the cloud shield contains precipitation echoes.

(b) How translation of cloud patterns compares with motions of radar echoes.

(c) Whether rotating echo patterns always relate to cloud vortices and vice versa.

(d) Whether the radar precipitation pattern remains unchanged during the 24-hour period between orbits over the same area on which photographs of cloud cover appear very similar.

(e) The lifetime of precipitation echoes of various types.

(3) All available synoptic observations, both surface and upper air as well as pilot reports and weather reconnaissance observations within significant range of the radar will be used to confirm or deny interrelationships between satellite and radar observation. In these studies the limitations of both radar and visual detection of precipitation due to distance, vertical extent, and intensity of the precipitation will be taken into consideration.

(4) An attempt will be made to establish parameters for identification of probable regions of precipitation in satellite-viewed cloud cover. Any potential operational applications will be discussed.

II RELATIONSHIPS BETWEEN CLOUD PHOTOGRAPHS AND PRECIPITATION PATTERNS

A. Synoptic Compatibility

1. Flow Patterns

To investigate whether localized regions of given synoptic patterns bear like relationships between satellite-viewed cloud cover and concomitant radar-viewed precipitation patterns, we categorized our sample of 122 days according to the surface and 500-mb wind direction over the station (or stations) at which the cloud-cover radar-echo relationships were being studied. Using the 500-mb maps closest to satellite passage we fitted each 500-mb map into zonal flow, meridional flow, or closed circulation centers. Then for each of the three 500-mb patterns we subdivided the concomitant surface charts according to the wind direction. Figure 2 illustrates the nine combinations found to exist in the sample studied.

In a broad sense Categories a, b, and c on the figure have predominantly westerly flow at the 500-mb level. This westerly flow may be due to zonal flow over the entire area or the specific station may be at the minimum point of a trough or at the maximum point of a ridge. The surface flow with these three categories is northwesterly, westerly, and southwesterly, respectively.

Categories d, e, f, and g have more meridional flow at the 500-mb level either northwesterly or southwesterly. The direction of the flow at the surface with Categories d, e, and f is northwesterly, southerly, and southwesterly, respectively, while with Category g there is variable wind direction around a closed high-pressure area.

The final two categories (h and i) exemplify blocking anticyclones and closed cyclonic circulations respectively.

Tables I and II list the category into which the 0000* maps for each day were placed and a summary of the number of days each month in each of the categories.

*All times in this report are GMT.

Table I

CLASSIFICATION OF 0000 GMT SURFACE AND 500-mb CHARTS

	Month				
Day	February	March	April	May	June
1		c	d	d	b
2		e	d	d	f
3		i	d	b	h
4		i	a	a	h
5		i	a	d	h
6		i	d	g	h
7		i	d	g	i
8		h	d	b	i
9		h	d	g	b
10		h	d	g	e
11		h	d	c	i
12		h	d	g	i
13		h	a	i	i
14		h	i	g	i
15	b	h	i	f	b
16	c	h	i	a	d
17	c	b	i	a	
18	f	g	i	e	
19	f	g	c	i	
20	b	c	i	d	
21	e	f	b	d	
22	d	g	c	g	
23	g	g	f	g	
24	c	g	f	g	
25	f	d	f	f	
26	c	d	e	c	
27	d	d	f	e	
28	g	d	b	i	
29		b	b	d	
30		i	i	g	
31		i		g	

Table II

NUMBER OF DAYS WITH VARIOUS FLOW PATTERNS

Month	Flow Pattern a	b	c	d	e	f	g	h	i
February	0	2	5	2	1	2	2	0	0
March	0	2	1	4	1	2	5	9	7
April	3	4	2	9	1	4	0	0	7
May	3	2	2	6	2	2	11	0	3
June	0	3	0	1	1	1	0	4	6
TOTAL	6	13	10	22	6	11	18	13	23

2. Precipitation Types

Radar films were examined for each day during the period studied to determine whether or not there were precipitation echoes at, or close to, the time of the satellite photographs. When echoes were present, the appearance of these echoes, from two hours before to two hours after satellite passage, was examined together with the cloud configuration shown by the satellite photographs and the locations of frontal systems as given by the 0000 surface maps prepared by the USWB office at San Francisco International Airport. From this evidence the radar echoes were classified as to whether they were produced by precipitation associated with frontal systems (either warm fronts or cold fronts), or by air-mass shower-type precipitation. In this examination of nearly concurrent radar, satellite, and map data, it was found that on occasion the analyzed positions of fronts did not correspond closely to the locations of cloud bands. The reason for this lack of correspondence may be threefold. First, the map analysts did not have access to the satellite photographs and, lacking other data in the vast Pacific Ocean, could not determine precisely the locations of fronts. Secondly, the time difference between the satellite photographs and the 0000 surface map could, depending on the speed of movement of the frontal systems, make a difference between the positions of photographed cloud bands and analyzed frontal systems. Finally, there is the possibility that the pre-completed grids for some of the satellite photographs may not be correct due to timer malfunctions in the picture-taking sequences, so that the indicated geographical location of a frontal band on the gridde satellite photograph is not the true geographical position. Throughout this report, when there is an apparent disparity between analyzed fronta positions (based often on very sparse data) and frontal positions based on cloud features and radar data, mention will be made of this disparity to point out how the additional data can be used to supplement conventional synoptic data. However, it is not unlikely that some differences could exist between the location of analyzed fronts (based on pressure, wind, and temperature) and the location of clouds and radar echoes. For example, Ligda[7] found differences in frontal location as determined by map analysis in contrast to radar positioning in the central United States where abundant data permit accurate frontal location. In additio to frontal precipitation and showers, there was also one day within the 122-day sample on which the echo appeared to be associated with squall line activity--i.e., there was a band of large, distinct convective cells some distance ahead of a cold front.

Table III lists the frequency of:

(1) Echo from frontal precipitation (either warm or cold)

(2) Echo from air-mass convective cloud cover

(3) Absence of echo.

This table shows that the occurrence of, or lack of, echoes is not restricted to any unique combination of winds at the surface and aloft, although there is a tendency toward more frequent occurrence with some flow patterns than with others.

3. Representative Regimes of Cloud Cover and Rainfall

Examples of the cloud cover and echo patterns from each of the categories have been chosen. Generally, the case illustrated is one of the most frequently occurring precipitation echo types in the flow pattern under consideration. For each example presented, the

Table III

FREQUENCY OF ECHOES FROM FRONTAL
OR AIR-MASS PRECIPITATION WITH VARIOUS FLOW PATTERNS

	Flow Pattern									Total
Echoes From	a	b	c	d	e	f	g	h	i	
Warm-Frontal Precipitation	0	0	2	1	3	3	3	0	1	13
Cold-Frontal Precipitation	5	4	2	5	1	6	2	1	16*	42
Air-Mass Shower Precipitation	0	5	2	11	0	0	3	1	3	25
Little or No Echo	1	4	4	5	2	2	10	11	3	42

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*One apparent squall line and four days with rotating echoes at a low pressure center.

following are given: a surface and 500-mb map, a sounding, one or two TIROS photographs (with superimposed grid containing latitude and longitude lines, fronts, and area of radar coverage), and one to three radarscope photographs for those situations in which there was precipitation. In the choice of cases for illustration we concentrated on the picket ship stations rather than coastal stations, since over the oceans "ground" clutter around the stations is much less. Thus, radarscope photographs did not have to be retouched to mask out echoes that were not from precipitation.

Flow Pattern a (westerly flow at the 500-mb level and northwesterly flow at the surface) occurred six times, and of these six times one had little or no precipitation and the other five had echoes apparently from cold-frontal precipitation. Figure 3 illustrates a typical example of the clouds and echoes with one of the cold fronts. In this case the cold front is moving southward on the east side of a high-pressure area and the low center is far to the northeast. The two radar stations in the vicinity of the front show banded echo, which at PS 1 (Picket Station One) is detectable to 120 miles and at PS 3 to

80 miles.* The sounding at PS 3 is moist, with dew-point depressions less than 6C up to the 400-mb level, above which dew points are not reported. At both stations the surface observers reported an overcast o low cloud. The 2100 observations were 10 Sc 10 at PS 1, and 10 St 15 at PS 3 (see Table IV for explanation of cloud codes). Neither statio reported precipitation at 2100, since at PS 1 light drizzle ceased between 1500 and 1800, and at PS 3 no precipitation was reported even when the echo band was over the ship.

Examination of the radar precipitation patterns at PS 1 shows echoes (to the north** and southwest of the ship) that would, if connected, form a band. Since no echo is detected within 40 miles of the radar it appears that precipitation-size particles do not exist within the height interval scanned. To test this hypothesis it is necessary to examine the height of the radar beam at various distances from the radar station. Figure C-1 (Appendix C) shows the position of the radar beam in the atmosphere as a function of distance from the radar station According to the figure, the beam would be filled by cloud--i.e., both the base and the top of the beam would have reached the reported cloud base at a range of 40 miles. The height of the beam increases with distance, and at 125 miles (where echo is no longer detected), the top of the beam is at 18,300 feet.† At this altitude the sounding still shows small (less than 6C) dew-point depressions, so the absence of echo may be due to the lack of precipitation-size particles above this level. Since there is no echo within the range interval where the radar beam is below the cloud base it appears that the echo between 40 and 125 miles may be from dense cloud from which no precipitation is falling.

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*All miles are nautical.

**The echoes are oriented so that north on the radarscope is parallel to the meridian through the radar station on the satellite photograph

†See Fig. C-1.

Table IV

EXPLANATION OF CLOUD CODES

10 Sc 10

Height of base in hundreds of feet

Abbreviation of cloud type

Number of tenths

Cloud Type	Abbreviation
Altocumulus	Ac
Altocumulus Castellanus	Acc
Altostratus	As
Cirrocumulus	Cc
Cirrostratus	Cs
Cirrus	Ci
Cumulonimbus	Cb
Cumulonimbus mamma	Cm
Cumulus	Cu
Cumulus Fractus	Cf
Stratus Fractus	Sf
Nimbostratus	Ns
Stratocumulus	Sc
Stratus	St

The satellite photograph shows a northeast-southwest cloud band over PS 3 and just to the south of PS 1. This band has numerous narrow lines of brighter cloud within and parallel to the band. This structure was also apparent in the other four cold fronts in this category. Behind the band the cloud cover is more convective in appearance but the surface observations show that the cloud is predominantly stratocumulus. The echo at PS 3 is west of this station at the time of the satellite photograph. According to the 0000 sounding at PS 3, the station was still in the warm air 3 hours and 26 minutes later. Subsequent radar data showed shower-type echoes within this area of cellular clouds. [Figures 13(a) and (d) show echoes from the cold fro of precipitation superimposed on the clouds.]

In summary, this type of flow pattern typically has a southw moving front with no deep trough aloft. The frontal position is indicated by a band of cloud whose upper surface is furrowed and which is dense enough to give good radar echoes even though any surface precipitation may be so scattered that a single ship would not experience rai fall during frontal passage.

<u>Flow Pattern b</u> (westerly flow both aloft and at the surface) was observed a total of 13 times. Five of the cases had shower-type echoes, four had echoes from cold-frontal precipitation and the remaini four had little or no precipitation. The case chosen for illustration is one of the shower situations. The surface map (Fig. 4) shows a shal trough along 140°W. At the 500-mb level the flow is predominantly westerly over the entire area. The cloud photograph in Fig. 4 shows an area of stratiform-appearing cloud northwest of PS 3. Most of the area however, has clouds of a cellular nature that tend to form northeast-southwest lines. The surface cloud observation at PS 3 at 2100 showed ten-tenths of towering cumulus with bases at 1500 feet, and heavy rain showers were reported in all quadrants. At PS 5 two cloud layers were observed; these were eight-tenths of towering cumulus with bases at 1500 feet and two-tenths of altocumulus (formed by the spreading out of cumulus) with bases at 9000 feet. A light rain shower was reported at PS 5 beginning at 1930 and ending at 2015.

The sounding at PS 5 shows a steep lapse rate from the surface to an inversion based at the 815-mb level. There is considerable moisture up to the inversion and then a rapid decrease in dew points above the 800-mb level.

The radar echoes at both PS 3 and PS 5 are of a showery nature. At PS 3 they are detected to ranges of 50 miles while at PS 5 they are detected to nearly 100 miles. This difference in range of detection at the two stations cannot be immediately explained from the satellite photograph. There appears to be more cloud at PS 3 than at PS 5, but since PS 3 has ten-tenths of towering cumulus, no upper cloud can be observed. At PS 5, which had only eight-tenths of towering cumulus, two-tenths of altocumulus is visible. These altocumulus clouds (formed by the spreading out of cumulus) had bases at 9000 feet. The center of the radar beam reaches 9000 feet at 95 miles. Therefore it would appear that the showers around PS 5 are in a more mature stage than those at PS 3 and that there is echo from the upper regions above 9000 feet where some of the towering cumulus appeared from surface observations to be spreading out into altocumulus. This is in spite of the fact that the PS 5 sounding is moist to only 6000 feet and that above this level dew-point depressions are about 18 degrees.

The Type b flow patterns in general had relatively little echo. The four cold-front cases had relatively well-defined frontal bands but the echoes were of a showery nature instead of elongated bands. The other four shower situations showed convective type cloud cover, but they were not as well defined as the case illustrated. The four cases with little or no echo had no distinctive cloud cover.

Flow Pattern c (westerly flow at the 500-mb level and southwesterly flow at the surface) occurred 10 times. Of these 10 times, two had echoes from warm-frontal precipitation, two had echoes from cold-frontal precipitation, two had shower-type echoes, and the remaining four had little or no echo. The case chosen for illustration in Fig. 5 is one of those classed as a cold front. The surface map shows the front extending from Vancouver Island southwestward across 35°N 120°W to a low center that is outside the area covered by the map.

The radar at PS 5 shows a widespread mass of stratiform type echo that is detectable to 140 miles. At this distance the base of the radar beam is at 12,000 feet or just above the 650-mb level. The echo extends in to the center of the scope, so there must be precipitation (or dense cloud) from the surface to some level above 12,000 feet. The observer at PS 3 reported an overcast of stratus or stratocumulus with bases at 2500 feet for a period of six hours before and after satellite time. At 2100 he also reported light drizzle.

The sounding shows much moisture up to the 870-mb level, and then a drier layer as evidenced by a dew-point depression of 15C at the 830-mb level. Above the 750-mb level it is again moist up to the 400-mb level, above which no dew points are given. This sounding supports the probability of cloud cover up to high levels and the surface observation of drizzle confirms that precipitation is falling from the cloud. (Sevel hours later, from 0400 to 0710, the observer reported heavy continuous rain.)

The satellite photograph shows only a small portion of the cold-frontal band. (Figure B-7 in Appendix B contains additional photographs of this frontal band.) The section of the band shown in Fig. 5 is relatively bright, although the brightest areas are rather irregular and are interspersed among areas of less bright clouds. While the cloud photograph gives no direct evidence indicating whether these are only low clouds or whether multiple cloud layers are present, it may be assumed from the sounding and the radar echoes that there are clouds extending from near the surface to high altitudes.

The other situations with this type of flow pattern that had extensive radar echoes also had rather distinctive cloud cover. That is, the other frontal situations had well-defined frontal cloud cover within which the presence of brighter, more convective areas would suggest the presence of precipitation.

In both the shower situations and the situations with little or no echo the cloud cover was rather stratiform or composed of very small, indistinct cells. Thus, knowledge that there was southwesterly flow at the surface (bringing warm air northward) but no fronts in the vicinity should lead one to expect very limited precipitation within the cloud cover.

Flow Pattern d (northwesterly flow both at the surface and at the 500-mb level) was quite frequent, occurring 22 times. The case chosen for illustration (Fig. 6) is one of the 11 shower situations. The surface map shows northwesterly flow over the network with a frontal system moving southward just west of PS 5. However, it appears from the satellite photograph that the front was over, or possibly just southeast of, PS 5 at 2102, in which case the front would have been some distance southeast of the station by analysis time, 0000 10 April. The cloud photograph shows an area of stratiform cloud in the area of the front while the remainder of the area is covered with typical cold-air-mass convective cloud cover. At 2100 the surface observer at PS 1 reported 8 Cb 14. He further reported precipitation within sight reaching the "ground," near, but not at, the station. At PS 3, at the same time, the observation was 6 Sc 20. Although showers were reported at PS 3 earlier, there were none after 1310. At PS 5 there was no observation at 2100 but the 1800 and 0000 observations both showed two-tenths of cumulus and one-tenth of altocumulus. At this station also, no precipitation was reported close to satellite time.

The radar echoes at PS 1 are widespread and are detected to ranges of between 100 and 125 nautical miles. At the latter distance the base of the radar beam is at 10,000 feet, so at least some of the cloud tops must be above this altitude. A sounding at PS 1 at 1200 on the 9th (there was no sounding at PS 1, PS 3, or PS 5 at 0000 on the 10th) shows a steep lapse rate with high moisture content up to the 700-mb level. Above the 700-mb level it is drier with dew-point depression of around 15C.

At PS 3 the radar shows less extensive shower activity and generally smaller echoes than those at PS 1. [Figures 14(a) and (d) show in more detail the relationship between these shower echoes and clouds by means of overlays.]

The other 21 days in this category showed a variety of echo patterns and cloud patterns. The majority of the other 10 cases with shower-type precipitation had well-defined cumuliform cloud cover. This cloud cover showed convective elements ranging in size from those on 9 April to much smaller elements with only small echoes at close range. Three of the cases with little or no echo also had small cellular type clouds. The cold-front cases all had well defined frontal bands with postfrontal convective clouds. The one warm-front situation had a front that lay parallel to the 500-mb contours, and extensive banded echo was observed in the vicinity of the front.

In general, the 22 days in this category were situations in which the appearance of the cloud cover--i.e., well-defined convective clouds or well-defined frontal bands--was such that the presence of precipitation would be strongly suspected.

Flow Pattern e has southwesterly flow aloft and southerly flow at the surface. There were only six days that could be placed in this category, and on three of these days warm-front-type precipitation occurred. On two other days there was a warm front to the west of the network but it was too distant for any of the ships to detect precipitation at satellite time. The situation classified as a cold front (20 February) was found (see Fig. B-2, Appendix B) to have a complex frontal structure and could probably also be considered as primarily a warm-front type. It is natural that these flow patterns would tend toward warm-front situations since the southerly winds would be carryin warm air northward, and the network is between the downstream ridge and the upstream trough.

The surface map in Fig. 7 shows a warm front extending from a low center southeastward into the network between PS 3 and PS 5. At the 500-mb level the ridge line is just east of the picket ship network so that west of 135°W there is southwesterly flow. Radars at PS 3 and PS 5 show widespread echoes. At PS 3 there is echo in all quadrants to 100 miles while at PS 5 the echo is detected northwest of the station to 140 miles. The satellite photograph shows a widespread area of clou within which there are numerous brighter and darker areas. PS 5 is on the southern edge of the cloud area while PS 3 is centrally located. There is a change in the appearance of cloud cover over PS 1, and radar data (not shown) from PS 1 showed a northwest-southeast line of precipitation echo 60 miles southwest of the station with more echo southwest of the line. The line was detectable to 150 miles west of the station. It seems likely, therefore, that the entire cloud area from PS 1 to PS 5 contains patches of echo similar to those within range of the radar at PS 3.

Surface observations at PS 3 and PS 5 at 2100 showed 10 Sc 20 and 10 St 10 respectively. PS 3 reported light rain showers at 1800 and 2100, while PS 5 reported rain during the previous 6 hours at both 1800 and 2100.

A sounding at PS 5 (there was no sounding from PS 3) at 0000 on the 25th (when the cloud observation was 10 Sc 15) shows a shallow, moist surface layer, then dry from the 950-mb level to the 780-mb level, and then a deep, moist layer extending to the 300-mb level. With a deep, moist layer such as this, clouds probably extend to high altitudes. With knowledge that a cloud cover of this type was associated with a deep, moist layer ahead of a warm front, one should suspect substantial widespread precipitation.

Figure 8 shows a second example of echoes from warm-frontal precipitation. In this situation there is a small cyclone at 43°N 141°W, with a warm front extending southeastward from the center to 36°N 135°W. At the 500-mb level there is a low-pressure center just south of Ocean Station "Papa" and a ridge just east of the line of picket ships. The cloud photograph shows a cold-frontal band extending southwestward from the position of the low center. It appears from the satellite photograph (which is three hours before map time), that the frontal system is further advanced than shown by the analysis, and that occlusion has already taken place. However, there is no immediately available way of estimating the gridding error in this particular case. There is widespread cloudiness in the vicinity of the low center but this cloud cover does not show the spiral configuration that is typical of mature systems. Generally, when a well-defined vortex is evident there is no longer a well-defined warm front. In this case there is evidence of a line of cloud extending southeastward from the low-pressure area and a clearer region between this band and the cold-frontal band. This clearer area (near 35°N 140°W) could be the warm sector of the system.

The radar at PS 5 shows an extensive precipitation echo out to ranges of 125 miles. (An hour later there was echo to 150 miles.) The echo extends nearly to the center (and subsequently moved across the center), so there must be a deep layer of dense cloud or precipitation from the surface to quite high altitudes.

The sounding at PS 5 shows considerable moisture up to the 400-mb level, above which moisture is not reported. There is an inversion at the 800-mb level and a thin layer of less moist air. This sounding, like the preceding one, is quite warm, and the zero-degree isotherm is at the 650-mb level.

The surface observations from PS 5 at 1500 and 1800 were 9 Sc 20, and at 2100 there was 10 Sc 20, while at 0000 and 0300 the observation was 10 St 20.

No precipitation was reported at the ship on the 17th or 18th (precipitation was reported only four times during the month this ship was on station). Other ships in the general area did, however, report precipitation around this frontal system. It would seem likely from the radar echoes and the sounding that there were extensive upper cloud layers hidden from the observers' view by the layer of stratocumulus with bases at 2000 feet. The top of the radar beam at 140 miles is 21,000 feet, so there must have been radar-detectable particles to nearly that height. At the 400-mb level (23,500 feet) the dew-point depression was 3C, or much less than the 6C difference that is accepted as indicating a high probability of the existence of cloud.

This case, therefore, as well as the previous one, shows the existence of widespread precipitation through a considerable depth of the atmosphere. The clouds within which this precipitation is embedded can be identified by recognizing that they are associated with the warm front of a developing cyclone. [Figure 13(e) shows the echoes from warm-frontal precipitation superimposed on the cloud photograph.]

Flow Pattern f (southwesterly flow both at the surface and at the 500-mb level) occurred 11 times. The case chosen for illustration is one of the cold-front situations. The surface map in Fig. 9 shows a cold front with waves extending in a north-south direction between 135°W and 140°W.

The cloud photograph shows a band of clouds along the analyzed position of the front with a protuberance, apparently associated with a wave, extending westward along 35°N. PS 3, on the western edge of the band, has radar echoes from 45 to 125 miles to the southeast while PS 5 on the eastern edge of the band has echoes to the west. At the latter station the echoes form a narrow north-south band about 75 miles west of the ship and the echoes are detectable to 100 miles. Both the satellite photographs and the radar echoes indicate that the front lies between PS 3 and PS 5, rather than west of PS 3 as shown by the surface analysis. According to the sounding, PS 5 is in the warm air.

At PS 3 at 1800, light rain, very light drizzle, and fog were reported together with an overcast of stratus with bases at 2000 feet. By 0000 on the 19th, multiple cloud decks were visible as follows:

2 Sc 20   3 Ac 80   2 As 100   2 Ac 120   .

Six hours later the only clouds visible were three-tenths of stratocumulus with bases at 3000 feet. Thus, in the vicinity of PS 3 the band was apparently composed of multiple cloud decks from which precipitation was falling, and there was substantial clearing after the passage of the band.

At PS 5 no precipitation was reported, and from 1500 on the 17th through midnight on the 18th the cloud observation was 10 Sc with bases varying between 2000 and 2500 feet. The sounding at PS 5 is quite warm and shows a moist surface layer extending up to the 850-mb level (about 5000 feet), and then a dry layer extending up to the 500-mb lev Above the 500-mb level there is considerable moisture, as indicated by the small dew-point depressions. The dry layer at PS 5 makes question the existence of middle cloud decks but there could be clouds above th 500-mb level. In all probability this dry layer did not extend westwa to the area where radar echoes were being detected.

The other ten cases in this category were divided among warm fronts, cold fronts, or little or no echo. The three warm fronts had well defined warm-frontal cloud bands and extensive radar echoes. The six cold-frontal situations generally had recognizable frontal cloud bands and extensive radar echo within the cold-frontal bands. The two cases with little or no precipitation also had frontal bands evident i the cloud photographs. In one case the front was too far to the west for precipitation to be affecting the network. In the other case, the frontal band was quite diffuse and did not have the appearance of a rain-bearing cloud.

Flow Pattern g has northwesterly flow at the 500-mb level an a high-pressure area at the surface. This type was evident on 18 of the 122 days studied and 10, or over half, of the cases had little or no precipitation. The remaining 8 cases consisted of 3 warm fronts, 2 cold fronts, and 3 situations with shower-type precipitation. Figure shows one of the cases of little or no precipitation. The surface map shows a high-pressure area centered just west of PS 5 while the 500-mb chart shows a ridge just to the west of the line of ships with predominantly northwesterly flow over the network. As indicated on the figure there were no echoes at OSP, PS 1, PS 3, and PS 5 and there wer no data at PS 7 and PS 9.

The cloud photograph shows a clear area west of PS 5 that is probably due to subsidence near the center of the high-pressure area. East of this clear area there are numerous small, closely spaced cellu cloud elements, none of which contain precipitation. Over OSP (which has southwesterly flow both at the surface and aloft) there is stratif cloud cover that extends eastward to PS 1. This cloud is apparently t far removed from any fronts or low centers to contain precipitation. Cloud observations at 2100 from the various ships show single and multiple layers as follows:

OSP	5 Sc 20		
PS 1	1 Sc 25	5 Ac 80	1 Ci/
PS 3	4 Cs/		
PS 5	2 Cu 20	8 Sc 55	.

A sounding at PS 5 shows a well-defined inversion at the 870-mb level and relatively large dew-point depressions throughout the sounding, although it is not extremely dry. The sounding is also quite warm, with the zero-degree isotherm at the 700-mb level. The other stations undoubtedly have similar soundings--i.e., a marked low-level inversion to limit the growth of any lower clouds and little upper-level moisture to support the existence of middle or high cloud layers.

The other 17 days in this category showed varied types of echo. The three warm-front situations had well-defined frontal bands and extensive echoes. The two cold fronts also had well-defined bands but the echo was of a showery nature. The three shower situations differed markedly from the Type d situations. The proximity to the center of the high where there may be subsidence apparently inhibits the growth of large cellular clouds so that the cloud cover is composed of very small, closely spaced cells with only small embedded showers. The nine other days with little or no precipitation had either gray stratiform clouds or numerous small closely spaced cellular clouds. The general appearance of the cloud cover--i.e., the stratiform nature or the small size of the cells--was such that one would not expect any precipitation of consequence within the clouds.

Flow Pattern h (high-pressure areas, both at the surface and aloft) was evident on 13 days during the period. On one of the days there was cold-front precipitation, on another day there were shower-type echoes. The remaining 11 days had little or no precipitation.

The surface map in Fig. 11 shows a ridge of high pressure extending northward between 135°W and 140°W. At the 500-mb level there is a closed high-pressure area between PS 1 and PS 3, with a closed low-pressure area south of Sacramento.

The cloud photographs show patches of stratiform clouds over and to the west of PS 3. Similar cloud cover extends southward to PS 5 Just east of PS 5 there is an extensive area of continuous stratiform cloud that extends eastward to the coast. It also extends southward across PS 7 but shows a more cellular structure in the vicinity of PS 7 Farther south the cellular structure becomes even more evident. Cloud observations from the ships were as follows:

PS 1	2100	4 St 10	1 Ci/		
PS 3	1800	9 Sc 12	(0000 clear)		
PS 5	2100	8 Sc 25			
PS 7	2100	9 Sc 20			
PS 9	1800	6 Cu 30	2 Ac 70	(0000	10 Cu 20)

These observations show that except at PS 9 there is a single layer of low cloud. At PS 9 some middle cloud was visible, and this middle cloud was coded as C_m 6 (altocumulus resulting from the spreadin out of cumulus).

There was no film from PS 3, but this station did not report any precipitation. At the rest of the stations there were neither rada echoes nor reports of any precipitation.

A sounding at PS 7 shows that there was an inversion just above the 900-mb level and that the air above the inversion was very dry.

The cloud cover shown here is typical of deep anticyclones--i.e., it has a very stratiform appearance and in many instances there are large, clear areas. Subsidence extending to quite low levels inhibits the vertical growth of clouds and confines them to a shallow layer close to the surface. In some instances they are confined to onl the lowest few hundred feet and are reported as fog.

Flow Pattern i (low-pressure areas both at the surface and aloft) was observed a total of 23 times. The types of radar-precipitation echoes observed with these closed lows depended on the position of the low with respect to one of the stations and also on the stage of development of the low. On 11 of the 23 days in this category the station closest to the low center showed the cold-front precipitation southwest of the low-pressure center. On one occasion warm-front precipitation extended across the closest radar station. Four of the low-pressure centers were located over the radar stations so that the echo observed was associated with the storm center and clearly showed rotation of precipitation around the center. On one day the radar station was in the warm sector southeast of the low, and a line of echoes similar to continental squall line activity was observed. The remaining six days were equally divided between shower type echoes and days with little or no precipitation. On these six days the low center was filling and the spiral cloud bands had nearly dissipated.

The case chosen for illustration is one in which the echo was associated with the vortex center. The surface chart in Fig. 12 shows a low-pressure area centered over PS 3. A warm front extends northeastward and a cold front is shown extending southeastward to 40°N, and then southwestward across PS 7. At the 500-mb level the low center is also located over PS 3.

The cloud photograph shows a well-defined vortex defining the location of the storm center. The cold-frontal band is also evident on the horizon. Three radar photographs from PS 3 show curved bands of precipitation echo. Comparison of the three photographs shows the rotation of these bands around the storm center which is about 60 miles east southeast of the ship in the photograph at 2314. A sounding from PS 3 shows near saturation up to the 600-mb level, and then a gradual decrease of moisture.

Surface observations taken during the period when the low-pressure area was moving over the ship are shown below:

Time	Clouds	Pressure (mb)	Wind (deg/kts)	Precipitation
0900	3 Ac 70	1039	040/05	
1200	1 Sc 20 10 Ac 70	997	360/17	
1500	10 Sc 20	952	020/23	
1800	10 Sc 20	902	360/25	Light continuous rain
2100	10 Sc 20	852	340/38	Light drizzle
0000	10 Sc 25	830	360/36	Light drizzle
0300	10 St 10	864	260/38	Light drizzle
0600	10 St 15	897	260/35	
0900	10 Sc 20	930	240/24	

The observations show that well ahead of the low there were only scattered middle clouds. By 1200 there was an overcast deck of middle clouds with only a few low clouds. During the remainder of the period only low clouds were visible. The lowest pressure occurred at 0000 on the 20th, and the winds were quite strong from 2100 to 0600. No heavy precipitation was reported; only light rain and drizzle were recorded.

The other 22 situations in this category generally had well-defined cloud patterns that could readily be associated with closed cyclonic pressure systems. The radar echo patterns varied according to the stage of development of the systems. The three cases of showers and the three cases with little or no echo were associated with systems in which the vortex cloud had degenerated into a poorly defined band of cellular clouds.

B. Comparison of Extensiveness of Echoes and Cloud Cover

In order to examine in detail the relative extensiveness of echo areas and cloud elements, a series of overlays was prepared. The echo pattern was distorted so it could be superimposed upon the cloud photograph. In the process of preparing these overlays it was found that in several cases the echoes did not fit the cloud pattern when they wer positioned according to the station location implied by the computer-generated grids. Since there was only one location within the cloud pattern where all echoes would fit within cloud elements, the echoes were used to regrid the satellite photographs. This substantiates the conclusions of Blackmer[8]--namely, "This use of radar echoes as landmarks should be possible in many other situations and may, therefore, make it possible to accurately position numerous cloud pictures which might otherwise not be useable."

The series of superimposed echoes on the cloud cover in Figs. 13 and 14 cover a range of types of cloud cover. The chosen situations include warm fronts, cold fronts, showers, and those with little or no precipitation. Figure 13 shows the relative extent of echoes and clouds in several frontal situations. Figures 13(a) and 13(d) show a frontal band extending across two of the radar stations. The PS 3 sounding made 3 hours and 26 minutes after photograph time indicates that the station was still in the warm air, presumably in advance of the front. The portion of the cloud band over the stations is a considerable distance from the low-pressure center and is composed of a number of individual narrow lines of brighter cloud. The precipitation echoes within this frontal band are localized narrow lines. In this case there was little precipitation reported by observers aboard the ships, so much of this echo appears to be only from dense clouds. The striated appearance of the cloud cover is very similar to that of the echo pattern when one discounts the limitations of the radar in detecting distant precipitation when the beam is well above the level of maximum potential return signal. The fact that the radar confirms the striated appearance of the cloud cover in this case demonstrates that this type of cold-frontal band is not a major precipitation producer and that bands such as this should be interpreted as being primarily dense clouds from which precipitation is minimal.

Figures 13(b) and 13(c) show cloud cover as photographed by both TIROS VIII and TIROS IX over the same area approximately 35 minutes apart. Differences in appearance of the clouds are most likely due to differences in the camera equipment aboard the satellites rather than short-period changes in the clouds themselves. The cloud photographs show a cold-frontal band, a warm-frontal band, and rifts in the clouds in the warm sector. The most extensive radar echo is associated with the almost isolated segment of cloud cover in the warm sector. The echo within both the warm-frontal and cold-frontal cloud cover is of a showery type and while the cloud cover remains fairly constant in time, the echoes show a definite decrease with time. Apart from this decrease the small amount of echo could be attributed to the fact that the height of the radar beam in the frontal zones could be so great that only the tops of the highest echoes were being detected. In this case, however, it seems more likely that the tenuous nature of the cloud cover together with the relatively small width of the bands is an indication that these clouds are not the type that contain copious precipitation. Figures 13(e) and 13(f) show rather widespread cloud cover within which the precipitation is quite extensive. In Fig. 13(e) especially the precipitation probably extends all through the area of cloud cover but the radar cannot detect it beyond about 140 miles. The difference in the appearance of cloud cover is reflected in the nature of the echo. In Fig. 13(e) the bright clouds seem randomly scattered over the area, as do the echoes. In Fig. 13(f) the brighter clouds are seen aligned in rows as are the echoes.

Figure 14 compares the relative extent of echoes and cloud cover of a more convective nature. Figures 14(a) and 14(d) show well-defined cellular clouds over a vast area of the eastern Pacific on 9 April. Careful inspection of the clouds shows that the elements are arranged in rings. The radar echoes do not form such complete rings as the cloud cover. The fact that the echo rings are not as complete indicates that (1) the cloud elements are in different stages of development, some actively precipitating, some probably not sufficiently developed for precipitation to have begun, and some probably dissipating; and (2) the cloud elements are not all the same height, so that at long ranges the radar beam is above the tops of the clouds of smaller vertical extent.

Figures 14(b) and 14(c) show convective cloud cover photographed by both TIROS VIII and TIROS VII only 31 minutes apart. The area around

15°N 135°W is included in both photographs. The same cloud elements in this area can be identified on both photographs, but there are variations in appearance that may be due to the relative angles of view, differences in resolution, and time changes in the cloud elements themselves.

Figure 14(b) shows a frontal band extending northeast-southwest across 40°N 130°W. The precipitation echoes around 40°N 135°W are not far behind the front, and the clouds do not show the well-defined rings that are common farther back in the cold air. In Fig. 14(c) the echoes show a greater variety of sizes than was the case in 14(a), 14(b), and 14(d). The cloud elements also seem to show a similar variety of sizes but this may be due to the better resolution of the TIROS VII cameras. (The same cloud cover photographed by TIROS IX at 2024 looked quite different, since the smaller cloud features were not distinct.) Many more of the cloud elements in Fig. 14(c) contain precipitation than was the case in Fig. 14(b). Thus, there is apparently an increase in precipitating clouds from immediately behind the frontal band upstream into the cold air.

Figure 14(e) shows a frontal cloud band extending across PS 9 at the southern end of the radar network. The radar echoes are from precipitation of a showery nature that is aligned in bands. The line of echoes within the cloud band east of the station did not vary in width as it moved across the radar scope. This implies that there was only a narrow band of precipitation that appears to be concentrated at the rear edge of the cloud. The cloud band over and west of the ship has showers throughout its entire width. The elongated echoes at the rear of the band correspond closely to the size and shape of the bright cloud elements.

Figure 14(f) shows echoes from two stations superimposed on a cloud photograph that shows a situation very similar to that in Fig. 14(b)--i.e., there is a frontal cloud band with postfrontal cellular clouds. The clouds within the frontal band are quite similar to those in Fig. 14(e); that is, they are of a showery nature and are aligned in bands. In the cold air behind the front there are ring-shaped clouds that have rather small echoes because the cold air is shallow.

These comparisons of echoes and cloud cover in Figs. 13 and 14 show differences in the distribution of precipitation within various types of cloud cover. In general, all precipitating clouds are bright on the corresponding satellite photograph; however, not all bright clouds are precipitating.

C. Distribution of Precipitation Around Maritime Cyclones

From concurrent cloud photographs and radar echoes in our data sample, we feel that it is possible to construct an operationally useful model illustrating the probable distribution of precipitation associated with the flow patterns illustrated in Fig. 2. Since the majority of the rainfall occurs with frontal bands and post-frontal showers associated with cyclonic storm systems, the model presents the type and distribution of precipitation to be expected within and surrounding the low-pressure area. We assume the center of the model to be the low center since it permits us to include the rotating echoes characteristic of this part of the low. The model then positions the distribution of echoes both upstream and downstream from the low and thus approximates the scheme of flow in the westerlies.

Figure 15 shows a well-developed cloud vortex, a cold-frontal band, and the convective clouds in the cold air to the rear of the cyclone. Radarscope photographs (none of which are for the same day as the satellite photograph) around the cloud photograph show typical echoes from precipitation that occur with the particular cloud cover in various quadrants of a typical storm. The lines connect the radar echoes with the cloud areas where they would be found. The three radarscope photographs labeled A show typical echoes close to the storm center. These echoes are from widespread areas of precipitation that exhibit a banded appearance, and these bands show a marked curvature. The second photograph is 1 hour and 48 minutes after the first, while the third photograph is 5 hours and 38 minutes after the first. During this time period the area of echo shows a counterclockwise rotation around the storm center. When a series of such radarscope photographs is viewed as a movie, the rotation of the precipitation echoes is apparent, and from the motion of these echoes the center of rotation may be precisely located. We find that this center of rotation is usually coincident with the surface low-pressure center.

A short distance from the center the echo is from an elongated band of precipitation, the width of which may be nearly as great as that of the cloud band. The echo labeled B in Fig. 15 is an example of the precipitation pattern within such cloud bands. At greater distances from the storm center the echo pattern generally shows a less solid precipitation area, and far from the storm center there may be only scattered shower-type precipitation associated with the frontal band. Ligda, Serebreny, and Nagle[9] found similar echo distribution around spiral echo patterns less than 100 miles in extent--i.e., sharp-edged echoes close to the center of the spiral, and diffuse echoes along the portion of the spiral arm farthest from the center.

In a vortex of the type illustrated, any remaining warm front is vestigial--indeed it is questionable whether there is any warm front with the majority of mature cyclones in the eastern Pacific. For purposes of completing the cyclone model, the echo labeled C (which is of the type usually found with warm fronts) is shown at the most likely point of the vestige of the warm front. These echoes are quite widespread and consist of intermingled areas of stratiform and convective-type precipitation. Such precipitation is most common with developing low-pressure systems in which the frontal structure tends more toward an open wave than an occluded system. As the system occludes, the warm-frontal cloud area usually decreases in size, leaving only a single frontal band of cloud extending from the vortex center.

A special feature of maritime cyclones is the existence of showers in the cold air to the rear of the storm center. Since the water is usually warmer than the air and since there is an abundance of moisture, numerous convective showers result. These showers are quite small at the leading edge of the cold air but become quite well developed where the cold dome has appreciable vertical extent. The radar echoes labeled D on Fig. 15 show small showers just behind the cold-frontal cloud band

and just west of the cloud bands surrounding the low center. An example of the precipitation echoes within the cold air well behind the cold front is shown by the radarscope photograph labeled E. These showers are quite large, and surface weather observations show that these may consist of copious rainfall, hail, or snow pellets, depending on the latitude and season. The presence of such showers over the ocean is in marked contrast to conditions over continents where cold air to the rear of cyclones lacks the necessary moisture (and, where there is snow cover the necessary surface heating) to form shower-type precipitation.

In summary, it may be said that in the vicinity of mature maritime cyclones there is precipitation both within the cloud spiral close to the storm center and within the convective clouds in the cold air behind the cyclone, and that it is nearly as extensive as the cloud cover. Wit developing systems there is widespread warm-front precipitation that, while not quite as extensive as the cloud cover, is interspersed among nearly all the area of the warm-front cloud cover.

III CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. General Conclusions

In considering the various types of cloud cover and attendant precipitation over the ocean in the order in which it might appear with the passage of a low-pressure area--i.e., warm front, warm sector, cold front, and finally post cold frontal--there are a number of conclusions that can be drawn concerning relationships between the clouds and precipitation. In determining such relationships one must consider that in maritime areas there is no terrain to cause vertical motions. Surface temperature and moisture content of air masses are modified by the relatively uniform sea surface, so that generally there is less contrast of air masses across a frontal boundary over oceans than over continents. Further, convective activity is less intense over extratropical oceanic areas than over continents, so there are no severe thunderstorms extending to 60,000 feet or more. Over continents such thunderstorm activity pumps much moisture from low to high levels, causing extensive cirrus anvils that persist for a long time after the convective activity has ceased. Because of these differences between maritime areas and continental areas, recognition of clouds that may be precipitating is easier over the oceans. In determining whether there may be precipitation within a given cloud cover it is necessary to examine cloud cover over a broad area in terms of flow patterns and synoptic features. Knowledge of these then permits focusing attention on smaller areas of clouds to specify whether there may be frontal precipitation, postfrontal showers, or little or no precipitation. The following conclusions are directly related to given synoptic parameters.

a. Warm Fronts

Warm-frontal cloud cover is generally restricted to those situations where the low center has not become occluded--that is, it is still an open wave. As the low center deepens, the warm front becomes less pronounced until, in a mature occluded cyclone there is no longer any well-defined widespread (satellite viewed) cloud system that coulc be identified as warm-frontal cloud cover. The precipitation distribu tion with warm fronts undergoes a similar change. When there is widespread warm-frontal cloudiness associated with an open wave the radar echoes show a widespread distribution of precipitation, often of an intermixed convective and stratiform nature over a large area. Often two or three adjacent radar stations show similar echoes, verifying that the precipitation is not localized, but is quite extensive. The precipitation, although it shows small-scale variations, is, in some cases, nearly as extensive as the cloud cover. The cloud cover may range between 15 degrees of latitude in extent in developing storms, down to only a few degrees as the warm front disappears in the deepeni of the cyclone. Knowledge that a cloud cover over a given area is the result of warm-frontal overrunning should lead one to suspect that the would be widespread precipitation and that the number and extensivenes of more convective-appearing cloud areas would indicate the extensiven of regions of heavier precipitation.

Since warm fronts are relatively infrequent it is obvio that warm-sector conditions would also be infrequent. When they do occur there seems to be a tendency for the cloud cover and precipitati to be more pronounced where the warm sector is quite narrow.

b. Cold Fronts

Cold fronts are quite frequent over the ocean and are generally well marked by a distinctive band of cloud. The widths of the bands are usually greatest closest to low centers and decrease wit increasing distance from the low center. The probable presence of pre cipitation appears to be indicated by the nature of the cloud cover of the band. In those instances where the cloud is bright and contains embedded regions of convective cloud, the probability of precipitation is high. On the other hand, when the cloud band is furrowed or has a striated appearance, the probability of precipitation is much lower.

c. Occluded Fronts

The surface frontal analysis usually showed an occluded frontal system with mature cyclonic storms. In our data sample, the cloud band associated with such systems did not show any discontinuity or distinguishing features at the point where the analyzed surface front was changed from an occluded front to a cold front. The cloud-precipitation relationships with occluded fronts appeared to be the same as with cold fronts.

d. Showers

Where there is cold air over warmer water, showers are quite common. These vary in size with distance behind the cold front. The largest cells usually occur where the cold air has the greatest vertical extent (usually under the center of the cold dome). The largest cells usually extend almost to the tropopause over the area of the cold air mass, and are growing in an environment in which the wind speed is usually less than 30 knots, with small variations in both speed and direction in the vertical. The size, extent, and brightness contribute to very unique cellular patterns easily distinguishable from the smaller rows and cells of cumulus clouds in closer proximity to the cold front.

The distribution of precipitation echoes is usually nearly comparable to the distribution of the largest, brightest cloud elements, especially when they are arranged in polygonal open cells. The comparison of distribution of precipitation echoes with smaller, less bright cloud elements is not as good. Even when these less-well-developed convective patterns are immediately to the rear of the cold front or interspersed among well-defined, large, bright cloud elements, precipitation echoes are often lacking. The presence or absence of radar-detectable precipitation falling from a deck of stratocumulus appears to depend on the temperature at the cloud level, precipitation being more likely from the colder clouds.

2. Specific Conclusions

The statements below are directly related to the questions posed in the statement of work (see Sec. I of this report), and are numbered accordingly:

(1a) The rainfall pattern very closely approximates the satellite-viewed cloud pattern under the following conditions:

- In vigorous convective cloud cells in a cold air mass well to the rear of a cold front
- Within a well developed spiral band around a mature cyclone center and outward along the frontal band when the band is bright and solid-appearing.

(1b) The lack of a patterned association is most apparent with the following:

- Blocking-type situations. In these cases there is no precipitation. However, the appearance of the clouds (or absence thereof) is a definite indication of the absence of precipitation. When cloud cover is present it is usually dull and tenuous and presents a rather flat-appearing upper surface.
- Southwesterly flow well ahead oi any fronts or near the centers of migratory highs where the cloud cover is a mixture of very small cells and patches of stratiform cloud, and there may be no precipitation or very small showers.
- Along portions of cold fronts at a considerable distance from low centers the precipitation may be in narrow bands or only scattered showers but the appearance of the cloud cover may not indicate which type.

(1c) The radar shows much detail in the precipitation pattern. The amount of this detail that is apparent in cloud patterns depends on the type of cloudiness, the type of camera equipment aboard the satellite, the altitude from which the photographs are taken, the angle of solar illumination, and the angle at which the cloud cover is viewed. With convective clouds, much of the radar detail is apparent in the cloud photographs. Toward the other extreme (widespread warm-frontal cloud cover and precipitation) where the radar shows an admixture of small, rather convective-appearing cells and larger diffuse patches of stratiform echo the cloud cover may show brighter areas much larger in size than the echoes and containing a range of echo sizes. Whether better cloud resolution and quantitative brightness measurements would show this detail or whether it is masked by upper clouds must await studies utilizing future satellite data.

(1d) Well-marked transitions of precipitation-echo type occur primarily near the leading edge of the cold air where the echo changes from banded stratiform to convective cells. The cellular clouds behind the frontal or vortex band clearly indicate this transition.

Close to the low-pressure center there appears to be a transition from a broad, single band of echo within the frontal cloud band away from the low center to multiple, curved bands of echo in the immediate vicinity of the storm center. The transition is not reflected by multiple cloud bands around the storm center probably because upper cloud obscures the lower precipitating clouds. The transition probably takes place where the cloud band starts to curve sharply north or northwest of the storm center.

(2a) The distribution of precipitation ahead of a storm system varies with the stage of development of the system. In a developing system that has well-defined warm-frontal cloud cover the horizontal extent of surface precipitation is nearly as great as the cloud cover. In very few instances was there an extensive single layer of upper cloud far in advance of the approaching precipitation (for a discussion of one case see Appendix B, Sec. 3-e). As a cyclone system begins to occlude, the warm-frontal cloud cover appears to decrease in size, but precipitation continues to fall from nearly all portions of the cloud cover. In a mature system with a well-defined spiral cloud band the horizontal extent of rainfall is comparable to the width of the cloud band.

(2b) The correlation between translation of cloud patterns and echo motions depends on the type of cloud cover. With convective-air-mass clouds, naturally there was perfect correlation. With other types of cloud cover it was often difficult to determine how various cloud features may have moved or changed during the

24-hour period between satellite photographs. If echoes were moving at 30 knots, the absolute maximum time that the precipitation echoes could be observed at a given station would be 10 hours (echoes moving along a 300-mile diameter of the radarscope). Then, unless the echoes were moving north or south along the line of ships, they could no longer be followed for comparison with the cloud pattern some 14 hours later. Generally, however, there is good correspondence between echo motions and the winds at the 700-mb level. Since these winds are not necessarily an indicator of the translation of systems but are more closely related to circulation around the system, the same should be true for echo motion and translation of cloud cover. In the extreme case, such as echoes in the north side of an eastward-moving cyclone, the echo motion would be exactly opposite to the translation of the spiral cloud band.

(2c) In all cases where rotating echoes were observed there was a cloud vortex near the station. There were no cases when a cloud vortex was over a station and there was not rotation of echoes. There were cases, however, when small vortices (vorticity centers) were observed in the area but not within range of a radar, so we do not know whether the precipitation around such centers would show rotation.

(2d) Generally due to translation of the pressure patterns, a given type of cloud cover would probably not be located over a given station on two successive days. One exception is extensive post-frontal convective cloudiness, a condition which could persist over a given station for several days. With such situations the echo pattern would show only minor changes (probably due to diurnal effects) during the 24-hour period between orbits over the same area. On other occasions, the cloud cover could go through some cycle of changes during the 24-hour period. For example, there might be a frontal band over a station, and then 24 hours later another similar-appearing frontal band over the same station with about the same echo pattern. During the 24 hours between orbits the echoes would have changed from frontal precipitation to showers, and then back to frontal echoes again.

(2e) Since radarscope photographs were taken at 15-minute intervals it was not possible to measure the lifetimes of echoes of shorter duration. With photographs taken at this rate only, the larger echo areas persisted (with minor changes) for a number of hours, in the majority of instances. One of the longest periods during which the echo was essentially unchanged was on 23 February (see Fig. B-5) when echo from continuous precipitation remained unchanged for 13 hours. In the case of convective showers the individual echoes change fairly rapidly but the <u>pattern</u> may persist for several days. In general, changes over maritime areas appear to occur less rapidly than over continents, and there is less diurnal variation.

B. Recommendations

The results of the research reported in this report are based on data collected during a relatively short time period and covering a relatively small geographical area. There were some departures from the mean circulation pattern during the months studied, but these departures varied from month to month so that the entire period was close to normal. Since the mean pattern for the area shows a high-pressure area centered just west of the network, the majority of the period studied would show cloud and precipitation associated with the flow on the east side of an anticyclone, if the normal pattern were dominant. Due to oscillations of the high-pressure area around its mean position and the passage of low-pressure areas through the network, the period studied includes all portions of cyclonic systems as well as numerous situations with showers on the east side of the anticyclone. The possibility exists that in other parts of the ocean where the mean circulation pattern is different from that in the eastern Pacific the cloud cover and associated precipitation would be different. For example, on the west side of the mean-high-pressure area, there could be fewer situations with shower-type clouds and precipitation and more situations with warm-frontal clouds and rainfall. The only way to confirm such a hypothesis is to study concurrent satellite cloud cover and radar echoes over other parts of the Pacific. Since no fixed networks exist for the collection of maritime radar data, the logical radar platforms would be U.S. Navy ships, such as aircraft carriers that have the necessary radar, meteorological personnel, and possibly equipment to receive APT photographs. Arrangements could be made to have personnel aboard such ships photograph radarscopes with 35-mm film for research purposes, and with Polaroid cameras for operational comparison of cloud cover and precipitation. Operational radar photographs would also prove useful in many situations for more accurately positioning the cloud photographs because with certain types of cloud cover (cold-frontal bands or showers) the echoes serve as "landmarks." Ships steaming eastward at approximately the same speed as a weather system could possibly monitor time changes in the precipitation pattern as the system deepened or filled. Such data on time changes would be quite useful for comparison with cloud photographs from synchronous satellites such as the recently orbited ATS-1. They would also make possible a valid assessment of the changes of weather systems as they approach the mountainous terrain of the West Coast. To date there has been no method of following a low-pressure area from the open ocean to the coast. Undoubtedly, interesting and important changes do take place, but fixed radar stations and once- or twice-a-day satellite photographs are inadequate for monitoring these changes.

In addition to the collection of data from other areas of the Pacific by moving ships, there is also much more that could be done with the data sample collected under the current contracts. Only a small portion of the entire period has been studied in great detail. There are many more days on which both the clouds and the echoes are of considerable interest. Studies of a climatological nature could be made. For example, the frequency and extent of echoes in various quadrants of the radarscopes at the various stations would show whether there are any significant latitude and longitude differences in rainfall between the various locations. Such studies would be confined primarily to data from the ships or to the maritime regions of coverage of the coastal stations, since the extensive ground clutter over the land areas of the west coast makes analysis of precipitation echoes difficult.

APPENDIX A

DATA AND PRELIMINARY ANALYSIS

APPENDIX A

DATA AND PRELIMINARY ANALYSIS

To obtain radar data from the various ships it was necessary to equip them with cameras and auxiliary equipment. Accordingly, the necessary hardware of a type found suitable during a prior radar-data-collection program with the U.S. Navy[10] was installed on the eleven ships manning the five radar picket sites and the two Canadian ships manning Ocean Station "Papa." By 15 February 1965, ships at the six ocean stations had been equipped, so the period studied began at 0000* on that date. Insofar as equipment limitations and the primary mission of the ships permitted, radarscope photographs were taken every 15 minutes around the clock. When the ships returned to port, the exposed film was returned to SRI for developing. Since the ships were on station for four or five weeks there was considerable time lag between the time when the radarscope photographs were taken and the time when the processed film was available for inspection. At the rate of photography mentioned above, one 100-foot roll of film contained about six days of radar records, so typically six rolls of film were exposed while a ship was on station. By the time the radar picket squadron was inactivated on 30 June 1965, some 115 rolls of 35-mm film 100 feet in length had been received from the ships. Additional film was also received from the two ADC sites and the two USWB sites.

TIROS IX data were received on 35-mm film, both positive for viewing and negative for making photographs. The film was received on plastic cores in lengths varying between 100 feet and 1000 feet. For ease of handling, it was placed on 100-foot spools that were labeled with the orbits contained therein. Additional TIROS IX data included grids for orbits over or close to the area of interest shown by Fig. 1 in the main text. The grids were punched and placed in looseleaf binders.

*All times in this report are GMT.

Supplementary data pertinent to the study included weather data, both in map and tabular form. First there were copies of the observations made aboard the ships. We received copies of the WBAN 11A and 11B forms giving surface observations and either copies of the WBAN 31 forms or copies of the message prepared for transmission of the radiosonde ascents. Second, we received selected maps and teletype data from the USWB office at San Francisco Airport. The maps included surface and upper air prepared at the airport and selected maps received via facsimile. Teletype data included hourly surface observations and radiosonde ascents for stations around the area of interest.

From this large mass of data it was then necessary to select for study a number of situations characteristic of the Eastern Pacific. The selection required consideration of a number of factors such as quality of TIROS photographs, completeness of radar records, and the availability and completeness of supporting meteorological data. In order to look at as much of the information for each day as possible to assess the suitability of the day for further study, the data were arranged in the following manner.

For each day, between three and seven satellite photographs over the network were printed (size 3-1/2 by 3-3/4 inches) gridded with clear plastic overlays showing latitude, longitude, and locations of radar stations, and mounted on a sheet of 17-by-22-inch paper together with the closest surface and 500-mb charts. These latter charts were 8-1/2 by 11 inches and covered the area shown by Fig. 1. A second 17-by-22-inch page was prepared containing radar data during the period two hours before to two hours after the time of satellite passage. If there were radar echoes during the period, five radarscope photographs were shown. (These were printed to a scale of 1 inch = 200 miles, or 1-1/2 inches on a side.) The time of the photograph, velocity of the echoes, and character and changes were recorded for each series of photographs. If there were no precipitation echoes at the station during the period it was noted in the space allotted on the sheet for the station. Other notations were made as required, such as "no film," "poor films," etc.

This data catalogue (a sample of which is shown in Figs. A-1 and A-2) covering the period 15 February to 16 June, was kept in looseleaf form so that it could be sorted into various categories on any selected criteria such as synoptic patterns, cloud types, or echo types as desired.

The selection of situations for detailed analysis was made on the basis of the types of situations and the quality and completeness of data on various days. Section II-A of the report deals with the frequency with which various flow patterns were observed over the network. The patterns may be very simply stated as either a low-pressure area moving through the network or the absence of lows due to an anticyclone over or adjacent to the network. Examples of both of these situations as well as transitions between them were studied.

There were variations in both the area covered by, and the resolution of, the TIROS IX photographs during the period studied. A considerable reduction in surface area covered was caused by the failure of one of the two cameras on 9 April. The resolution varied due to the elliptical orbit that resulted in periods during which high-resolution photographs were taken over the network at perigee and other periods when the satellite was over the network at apogee and the photographs were of much lower resolution. Photographs taken at apogee, however, did cover a larger area; hence entire storm systems were shown in one picture. An example of one such photograph is presented in Fig. 15.

The completeness of radar data depended on whether the radar was required for some purpose other than our radarscope photography program. Since the program was on a "not to interfere with the primary mission" basis there were times when no photographs were taken. At other times, malfunction of photographic equipment or improper scope settings resulted in data of low quality. Even with some situations not useable due to data limitations, there was still an adequate sample of all types of situations for a number of typical examples to be considered for analysis.

APPENDIX B

CASE HISTORY

APPENDIX B

CASE HISTORY

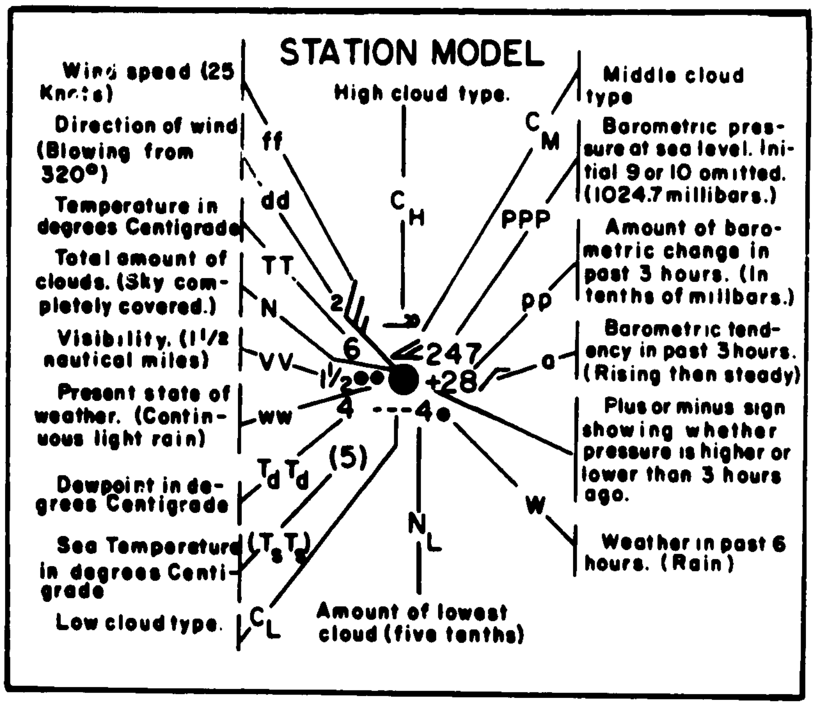
1. Introduction

Our study of the relationships between maritime precipitation radar echoes and satellite-viewed cloud cover required examination of all cloud cover--both precipitating and non-precipitating--over the radar network, in order to ascertain distinguishing characteristics of precipitating types of cloud patterns. One frequent condition is a chain of migratory cyclones moving along northerly latitudes and followed by anticyclones that push cold fronts southward across the network.

In contradistinction to the migratory systems there are often extended periods when a pressure system remains stationary over a given location. These stationary pressure systems may be either high-pressure areas (blocks) or low-pressure areas (cold, cut-off cyclones). Previous case histories discussed both of these types. A study of a cold, cut-off low over the network from 2 to 6 March 1965 was made by Blackmer.[11] A study of a blocking anticyclone over the network from 7 to 25 March was presented by Alder.[12] The case history presented below concerns migratory systems during the period 19 to 26 February.

Radar precipitation echoes were examined and photographs made to illustrate changes in precipitation pattern between satellite passes as well as the distribution of echoes close to the time of satellite passage. The synoptic situation is illustrated by surface weather maps and 500-mb charts as analyzed by the USWB office at San Francisco International Airport. (We have superimposed 1000-to-500-mb thickness lines on the 500-mb charts.) The legend on the following page explains the meaning of the lines and numbers on the charts. Available soundings near the radar sites have also been examined to show the vertical distribution of temperature and moisture (and wind when measured).

STATION MODEL AND LEGEND FOR ANALYSES



LEGEND FOR ANALYSES

COLD FRONT	
WARM FRONT	
STATIONARY FRONT	
OCCLUDED FRONT	
SURFACE ISOBAR	——1004 (millibars)
500mb CONTOUR	——550 (tens of meters)
500mb ISOTHERM	----°C
THICKNESS (1000-500mb)	●●●● (tens of meters)

2. General Description

Between the 19th and 27th of February the pressure pattern over the network showed a number of changes. On the 20th, there was a small high-pressure area at the northern end of the network with an east-west front across the center of the network. On the 21st, another cold front moved into the network and merged with the previous one. The combined frontal system moved southward and by 0000 of the 23rd was well to the south of the network and a large high-pressure area was centered over PS 5. From the 22nd to the 26th there was a quasi-stationary front with waves at the north end of the network, which on the 26th moved southward after a low-pressure area from the southwest moved across the network. The TIROS IX photographs during this period show, once a day, the cloud cover associated with this changing synoptic pattern. On many occasions there is small-scale detail that is difficult to interpret because of the sparsity of other meteorological data in the area. The fact that the cloud cover is viewed only once a day makes it impossible to determine exactly how various cloud features may have moved or changed to give the pattern that is seen 24 hours later. To make a better estimate of motion and changes of cloud features, radar data during the interval between satellite photographs have been examined and echo motions and changes determined. These motions and changes of the echoes from precipitation within the clouds thus provide clues to the structures, probable motions, and changes in the clouds themselves.

3. Detailed Discussion

a. 19 February

The satellite photographs taken at 2251 and 2253 along with maps, soundings, and radar photographs are shown in Fig. B-1. One major feature in the cloud cover is a vortex near 32.5°N 145°W. One portion of the cloud band extends from the vortex northeastward across PS 5 and N. Another portion extends from 40°N 145°W generally southward across 25°N 140°W. The band extending coastward across PS 5 corresponds roughly with the position of the front shown on the 0000 surface map for 20 February. North of the front there is a small high-pressure area with a center between PS 1 and PS 3. Cloud cover west of the high-pressure center is, according to the cloud photograph, virtually non-existent. Ships around the periphery of the clear area, with one exception, report an overcast of stratocumulus. The exception is the ship at 44°N 143°W with only scattered cirrus. South of the front the majority of the surface observations are of an overcast of stratocumulus. The satellite photographs show that the area is not uniformly overcast. Instead there is a region of less dense cloud between the cloud band along 140°W, and PS 7 and PS 9. Over the two picket ships there is an area of stratiform cloud that extends to the California Coast. Since it terminates at the coast, it is probably low stratus or stratocumulus.

A sounding taken at PS 1 at 0000 20 February shows a rapid decrease in temperature and dew-point depressions from the surface to about the 870-mb level. Above this level there is an inversion and a decrease in moisture up to the 800-mb level. Above the 800-mb level the temperature fluctuates considerably, and the air is relatively moist although dew-point depressions vary from 3C to 13C. The cloud observation at the time the sounding was taken was ten-tenths stratocumulus with bases at 2500 feet. It seems unlikely that these clouds extend above the inversion (870-mb level or about 4000 feet), so the cloud cover at PS 1 is probably only a single layer extending from 2500 feet to 4000 feet with no radar-detectable precipitation within it.

The sounding at PS 5 shows a deeper layer of moist air below a strong inversion, with marked drying just above the 800-mb level (about 6500 feet). The surface observation at this station was also ten-tenths of stratocumulus with bases at 2500 feet. This cloud deck is about 4000 feet thick and there are probably upper cloud layers since dew-point depressions above the 460-mb level are less than 4C. At 2315 the radar showed a small band of echo fifty miles north of PS 5. This band is detectable to almost 100 miles. Beyond 100 miles the base of the radar beam is above 6500 feet, so it would be above the level of the inversion shown on the sounding. The band of echo is very narrow and is not continuous but has small breaks in it. No precipitation was reported by the observer at PS 5 but the motion of the echo (from the west) is such that it would not pass over the ship. The cloud cover in the vicinity of PS 5 is an east-west band of brighter cloud some two degrees or 120 nautical miles in width. PS 5 is located on the southern edge of the cloud band, so the echo band is about in its center and has a similar alignment. Probably there is some light localized precipitation along the entire length of this band and also the band extending southward along 140°W. Subsequently, a small area of precipitation was detected southwest of PS 5 as shown by the radarscope photograph at 0816 on the 20th. This echo is probably associated with the band of cloud along 140°W.

At PS 1 an echo was first detected at 0415, and there were several echo areas on the PPI between 0415 and 1235. An example of the echo is shown at 1005 on the 20th. The photograph shows no echo closer than 30 miles. As the echo moved across the scope it would disappear at this distance, and reappear a similar distance downwind. This behavior implies that the echo may have been either dense cloud or precipitation aloft, and that at short ranges the radar beam was beneath the cloud base.

At PS 3 there was an area of echo within range from 1031 to 1203. The appearance of this echo is shown by the photograph at 1101 on the 20th, on which a small area of echo is visible 100 miles southeast.

b. 20 February

The satellite photographs on the 20th show (see Fig. B-2) several of the features of the previous day. Most notable is the band of cloud extending generally southward, east of the vortex center. Although the vortex center is less well defined, the cloud band is quite distinct and is about five degrees longitude farther east than on the previous day. The band that extended coastward across PS 5 on the previous day has moved northward toward PS 3. The area that was relatively clear the day before has decreased in width as the cloud cover with a poorly defined cold-front band moved into the area from the northwest. Prior to satellite passage there was some echo in the vicinity of the three northernmost picket ships. At satellite time there were only a few small showers around PS 1 out to ranges of about 25 miles, as shown by the radarscope photograph at 2245. A marked increase in the extent of these showers occurred between 0000 and 0200 on the 21st, and the observer reported light, continuous rain beginning at 0030. The rain continued intermittently until shortly after 1000. Echoes from this precipitation area are shown at 0405 and 0605 on the 21st.

At PS 3 the scope setting was such that only the most intense echo areas were presented. At this station rain began some time prior to the 0000 observation (at which time there was ten-tenths strato-cumulus with bases at 2500 feet). By 0600, precipitation changed from rain to drizzle that continued through the 1200 observation. The echo pattern close to 1200 is shown by the echoes at 1158.

The sounding at PS 3 taken at 0000 shows that the atmosphere is moist up to the level above which dew-point values are no longer re-ported (about the 360-mb level in this case). With this deep layer of moist air, it is very likely that upper clouds are present above the stratocumulus overcast, and these clouds may also extend across PS 1 since the appearance of the cloud cover over the two stations is similar in the TIROS photograph.

Further south at PS 5 the sounding at 0000 shows an inversion at the 900-mb level. The air is dry above the inversion, to about the 500-mb level. The cloud observation at the time of the sounding was nine-tenths of stratocumulus with bases at 2500 feet. The tops of these clouds are probably at the level of the moisture decrease, or about 3000 feet. With the considerable moisture above the 500-mb level there most likely is an upper cloud layer, but the observer reported none visible through the breaks in the lower cloud cover. The observer did not report any precipitation on the 20th or 21st even though the radar showed numerous small echoes to ranges of 50 miles or more (see radar photographs from PS 5 at 1645 and 2236 on the 20th, and at 0906 on the 21st). The fact that these echoes extend into the center indicates that radar-detectable precipitation particles exist from the level of the cloud base down to the surface. The cloud cover over PS 5 is variable, as indicated by the brighter and darker areas in the cloud photograph. There appear to be two cloud decks, one that extends across PS 5 from PS 7 and is probably stratocumulus. Small, brighter elements extend across PS 5 from the bright area of cloud to the southwest that is a part of the vortex cloud band. This latter may be upper cloud.

c. 21 February

By satellite time on the 21st the cold-frontal cloud band has advanced southward to a position just south of PS 5. Eastward it extends as far as the coast and then turns northward along the coast. The cloud photograph in Fig. B-3 shows some substantial changes from those on the previous day. The frontal band, which supposedly resulted from the merging of two frontal bands shown 24 hours earlier, has diminished in width to about 60 miles and the vortex is no longer apparent. At the time of satellite passage relatively little echo was observed by the ships. The most echo was at PS 7 where at 1319 on the 21st there was a small area 100 miles east southeast. By satellite time (see photograph at 2235) the area of echo extended from the center to about 60 miles east. This would place the echo within the relatively bright cloud element over PS 7. The sounding from PS 7 at 0000 on the 22nd shows a moist layer up to the 810-mb level, and then a temperature inversion and sharp decrease in moisture. The surface cloud observation at the time the sounding was made was seven-tenths stratocumulus with bases at 2500 feet and one-tenth cirrus, bases unknown. In addition, past weather during the previous six-hour period was given as rain showers. From the sounding and the reported clouds, it would appear that the stratocumulus deck extends from 2500 feet to 6000 feet (the top of the moist layer) and that scattered shower-type precipitation is falling from this deck. However, beneath similar-appearing cloud cover over PS 9 there was no precipitation echo. At PS 9 there was nine-tenths of stratocumulus with bases at 1500 feet and one-tenth of altocumulus with bases at 10,000 feet. According to the sounding at PS 9, not shown, the top of the lower cloud deck would be about 3000 feet for a thickness of 1500 feet--apparently too thin for precipitation since the temperature was well above freezing.

At PS 5, cloud observations close to the time of the satellite photograph gave eight- to ten-tenths stratocumulus at 2000 feet. There was no change in cloud cover from previous reports to indicate the passage of a narrow frontal-appearing cloud band. The winds, however, did shift from 300 degrees to 340 degrees between 2100 and 0000. Neither precipitation nor radar echoes were reported at this station. The sounding showed a moist layer to the 900-mb level or about 3000 feet, so the lower cloud deck was only about 1000 feet in vertical extent. The thinness of this cloud cover is readily apparent in the satellite photographs.

PS 3 is located within an area of cloud that appears to be composed of small, closely spaced cellular elements. The original radarscope photograph at 2229 shows a few light shower-type echoes that form a northwest-southeast band about 30 miles northeast of the ship. Northeast of the ship, there appears to be a complete overcast while to the southwest the spacing between the elements is larger. The surface cloud observation at PS 3 at 0000 was seven-tenths stratocumulus with bases at 2500 feet and two-tenths cirrus, bases unknown. In addition, light intermittent rain was falling and there had been showers during the preceding six hours. There was no sounding from which possible cloud tops could be inferred.

The cloud cover at PS 1 was eight-tenths stratocumulus with bases at 2000 feet and there were rain showers between 1900 and 0000. The radar showed (at 2231) a few small shower-type echoes close to the center of the PPI. The sounding at PS 1 shows a moist surface layer to the 915-mb level, then an inversion with moisture decreasing to unmeasurable values, and then a moist layer around the 700-mb level. The cloud deck would be about 1000 feet thick. While this is a thinner cloud deck than the one over PS 9, its temperature is much lower (and it seems to have a cellular structure similar to the cloud cover over PS 3), thus making it possible for showers to develop in this case.

d. 2? February

The satellite photographs in Fig. B-4 show a frontal band across PS 1 and extensive cloudiness ahead of the band nearly down to PS 5. PS 5 is near the center of a high-pressure area and it is relatively clear to the west and southwest of the ship. Between PS 5 and the coast and southward from PS 5 to PS 7 there is cloud cover composed of small, closely spaced convective cells. As the frontal band was approaching PS 1 some rather extensive radar echoes were observed. A series of radar photographs is shown in time-section form to illustrate changes in the echo pattern. The time of each photograph is indicated beneath the photograph. Time increases to the left so that later echoes appear to the west of earlier echoes to maintain spatial consistency. The photograph at 1317 shows an area of precipitation 50 miles west of the ship. By 1602 this echo area is centered over the ship and extends about 60 miles in all directions. At 1837, the area of stratiform echo has disappeared to the east and showers have moved in behind it. The shower-type echo is replaced after 2038 by another area of continuous echo that is centered over the ship at 2123. This echo also moves eastward and is last visible about 50 miles east at 2354. This sequence presumably represents echoes from warm-frontal clouds (1317-1722), warm-sector showers (1837-1906), and then echo from cold-frontal precipitation (2038-2354). The only reported rainfall from surface observations during the period was light continuous rain that began at 2120 and ended sometime prior to 0000, thus accompanying the cold-frontal passage. The reason no rainfall was reported during the period while warm-frontal echo was over the ship is not known.

At PS 3 the radar sequence shows echo about 75 to 100 miles west at 1402. At this station echoes appear as two bands oriented northeast-southwest. One passes the ship around 1700 and contains rainfall; the other is still west of the ship at 2304. The exact times of beginning of precipitation were not given on the WBAN 11B forms from PS 3, but the 1800 observation reported light continuous rain. An interpretation of the echo pattern at PS 3 would identify these echoes as probably pre-cold-frontal showers that have formed into lines. The satellite photographs, especially Frame 2 at 2225, show bands of brighte cloud, one east and one west of PS 3, with an alignment similar to that of the echoes. These cloud bands appear to merge together in the fronta band near PS 1. This hypothesis is supported by the absence of banded echoes at PS 1.

A sounding at PS 1 prior to the arrival of the warm-front echo shows a low-level moist layer up to the 870-mb level (about 4000 feet), then a very dry layer from the 850 to the 680-mb level, and then a shallow, moist layer with a second small inversion but much less moisture just above the 600-mb level. The surface cloud observation at the time of this sounding was ten-tenths stratocumulus with bases at 2200 feet; thus this cloud deck is about 1800 feet thick. Twelve hours later (at 0000 on the 23rd) a sounding at PS 1 behind the cold front shows again a low-level, moist layer. In this case the layer is dry from the 900-mb level to the 470-mb level, and the moist layer around the 600-mb level 12 hours earlier is absent. The surface cloud observation at the time of the 0000 sounding was ten-tenths stratocumulus with bases at 2000 feet. Since the sounding implies that the cloud top is at 3000 feet, the thickness of the cloud layer is only about 1000 feet. Probably during the interval between these two soundings there was a deeper moist layer with a thicker cloud deck from which the precipitation fell.

At PS 3, which is still in the warm sector at 0000, the sounding shows a very shallow moist layer at the surface (extending to about 1000 feet). At the 900-mb level the dew-point depression is 20C. The dry layer is relatively shallow and above the 830-mb level (or 5500 feet) the sounding is again quite moist with dew-point depressions less than 6 degrees. In all probability there are upper cloud layers between the 700- and 400-mb levels that cannot be observed because of ten-tenths stratus with bases at 1500 feet.

e. 23 February

By the time of satellite passage on the 23rd a wave was located west of PS 1. This wave formed on the cold front that was southeast of PS 1 twenty-four hours earlier. The front had not pushed southward because of the high-pressure area still centered near PS 5. The cloud photographs at 2214 and 2216 in Fig. B-5 show the extensive cloud cover with the wave and the edge of the cold-frontal band 5 degrees west of PS 1. Cloud cover in the warm sector is extensive and covers PS 5. There was a long period of rainfall at PS 1 during the passage of the frontal systems. Echo first appeared 50 miles southwest of PS 1 at 1035 on the 23rd, as shown by the sequence of radar photographs. This echo was in the form of ragged patches of precipitation until about 1710. From 1710 until about 0600 on the 24th the echo remained unchanged--i.e., there was an area of uniform echo (since the echo pattern from 1732 to 0605 showed no changes it has been omitted from the sequence) to about 50 miles from the ship. The echo area then moved eastward and by 0907 had nearly disappeared. Shortly thereafter a new area of echo moved across from the west, practically repeating the previous echo sequence and finally disappeared in the east at 1730 on the 24th. Surface observations of precipitation during the period show that light, continuous rain began at 1635 on the 23rd and continued until 1530 on the 24th. Cloud observations prior to and during the period of precipitation were:

2/23	0600	2 Sc 20	10 Cs
	1200	9 Cs	
	1800	4 Sc 20	6 Ac 80
2/24	0000	10 Sc 20	
	0600	10 Sc 18	
	1200	10 Sc 20	
	1800	10 Sc 20	

These observations show a cloud sequence that is typically associated with a warm front--i.e., extensive cirrostratus with little or no lower cloud, then middle cloud obscuring the upper layer, and finally a low overcast. Rain started an hour and a half before the 1800 observation and was apparently falling from the middle and upper cloud.

A sounding at PS 1 at 1200 on the 23rd (when the only cloud reported was nine-tenths cirrostratus) shows a very shallow surface layer that is drier than usual. It extends to the 950-mb level (about 1500 feet), and then becomes even drier up to the 670-mb level (11,000 feet). From this level to the 400-mb level the sounding is quite moist with cirrostratus above 11,000 feet. No sounding was made at 0000 on the 24th, but at 1200 on the 24th (when continuous light rain was still occurring) the sounding shows near saturation up to the 700-mb level, or about 10,000 feet. At the time of this latter sounding, the radar is detecting widespread precipitation only to about 50 nautical miles. The reason for this limited range of detection is probably that at distances greater than 50 miles the radar beam is in snow above the level at which the falling snow melts into rain. Since snow does not reflect the radar beam as well as rain, the particles in this case do not provide a detectable return signal. The sounding shows the zero-degree isotherm to be at the 830-mb level or at a height of 5500 feet. The top of the radar beam intercepts this level at a range of 55 miles, which is consistent with the maximum range of echo detection.

At PS 3 there were a few scattered patches of echo (similar to those shown at 0035) until 0340, and then no echo until 0715. From 0715 until 2100 there were areas of echo primarily north of the station. These echoes were of a showery nature and were detectable to a range of 100 miles. Examples of these echoes are included on Fig. B-5. Little precipitation was reported by the observer aboard PS 3 on the 23rd. At 0000 the observer reported rain during the previous hour, and then at 1800 he reported light continuous drizzle. At 0000 on the 24th he again reported rain during the previous hour. A sounding at 0000 of the 24th, when the surface cloud observation was ten-tenths stratus at 2500 feet, shows much moisture up to the 350-mb level, above which moisture is not given. The zero-degree isotherm on this sounding is at the 800-mb level, or about 6000 feet. The top of the radar beam reaches this level at 60 miles, which is less than the maximum range of detection of echoes. This implies that north of PS 3 there is shower activity extending to altitudes above the melting level while in the vicinity of PS 1 the precipitation is of a more stratiform type. Careful examination of the cloud photograph does not show any significant change in cloud cover between PS 1 and PS 3, although directly over PS 1 there is a transition from quite stratiform cloud to the north, to less stratiform cloud to the south. Apparently the differences in the lower cloud decks where precipitation is occurring are masked by more uniform upper clouds.

f. 24 February

During the next 24 hours, waves continued to move northeastward across the general vicinity of PS 1. At 2205 on the 24th there was a wave northeast of PS 1 and the cold front extending southward from the wave was approaching PS 3. The cloud photographs (see Fig. B-6) show the frontal band from just north of PS 1 extending southward to the vicinity of PS 3. From PS 3 southward and eastward to the coast the cloud cover has no organization; it consists of a mixture of cumuliform elements of various sizes with patches of more stratiform cloud. At PS 1 the radar was inoperative from 1928 to 2345 on the 24th. No precipitation echoes were observed after that time. The sequence of echoes at PS 3 shows the distribution of echoes up to and including the time of satellite passage. At 1048 there was scattered echo from 40 to 100 miles northwest. This echo gradually consolidates into a general northeast-southwest band that moves over the station at about 1600 and then disappears to the southeast. Subsequently, another more extensive band forms to the northwest, and at 2307 extends from about 25 to 80 miles northwest of the station. The cloud photograph at 2205 shows an area of brighter cloud very close to PS 3 just east of a narrow rift containing less dense cloud between the station and the broad frontal band to the northwest.

Surface cloud and precipitation observations from PS 3 on the 24th were as follows:

0600	3 St 25				
1200	2 Sc 25	2 Ac 80	4 Cs/		Light present rain shower and past rain showers
1800	2 Sf 10	3 Sc 20	3 As 80	2 Ac 100	
0000	6 Sc 20	4 Sc 30	Past rain shower		

The sounding at PS 3 at 1200 shows a moist surface layer up to an inversion at the 850-mb level, then a drier layer up to the 580-mb level, and then near saturation to the 450-mb level where the sounding terminates. The slightly moister layer as shown by a dew-point depression of 6C at the 750-mb level is at the reported base of the altocumulus deck. The layer of cirrostratus is somewhere in the moist layer above the 580-mb level (about 14,500 feet). The sounding at 0000, 25 February, is quite moist at all levels although there is a slightly drier layer just below the 700-mb level that is probably the remnants of the deep, dry layer 12 hours earlier. Close to this time the radar was detecting echo to about 100 miles. At this distance the base of the beam is at 6500 feet or close to the height of the zero-degree isotherm (780-mb or 7000 feet) as shown by the sounding. The lack of echo above the zero-degree level would indicate that the precipitation tends toward a more continuous type rather than the convective shower type. This is reflected in the photograph by the rather dull appearance of the cloud cover and the absence of distinct convective cells.

Further south, at PS 5, there were shower-type echoes, as shown by the radarscope photographs at 1404 and 2209. Radar operation at this station was intermittent on the 24th, but small showers like those illustrated appear to have been present most of the day although no precipitation at (or within sight of) the ship was reported. Cloud observations at selected times were:

1500	6 Sc 20	4 As 80	
1800	6 Sc 20	2 As 80	
2100	5 Sc 20	4 Ac 80	
0000	6 Sc 20	2 As 80	1 Cc/

A sounding at 0000 on the 25th shows a moist surface layer with an inversion and rapid drying above about the 875-mb level, or 4000 feet. The top of the radar beam reaches the top of this moist layer at 45 miles, which corresponds closely to the maximum range of detection of the majority of the echoes. Since the base of the radar beam does not reach the level of the cloud base (2000 feet) until it is fifty miles from the ship, the small echoes must be precipitation falling out of the stratocumulus cloud deck. The mixture of clouds in the vicinity of PS 5 in the TIROS photograph must, therefore, consist of a layer of stratocumulus from which some small showers are occurring. Above this lower layer there are apparently some altocumulus or altostratus and cirrocumulus according to the surface observers' reports before and after the TIROS photograph.

g. 25 February

During the next 24 hours the cold front pushed southward to a position north of PS 5 and cold air spread into the northern part of the network resulting in convective cellular clouds around PS 1. The cloud photographs (Fig. B-7) from Orbit 418 show the frontal band extending northeast-southwest between PS 3 and PS 5, with a sharp edge just over PS 3. The band extends southwestward to an apparent vortex near 35°N 145°W. About 5 degrees west of PS 5 there is a north-south band of convective-appearing cloud extending southward from the frontal band. Another similar band parallels the first about 5 degrees further to the west. Also of interest is the cloud configuration near 45°N 143°W. Bittner[13] refers to this type of cloud pattern as positive vorticity advection maxima ("PVA MAX") and describes it as a comma-shaped pattern of middle and high clouds found in the cold air to the south or southwest of a vortex and usually preceding a 500-mb short wave trough. Similar cloud patterns called vorticity centers, which consist of cumuliform lines and/or streets spiraling in toward a center, have been studied by Oliver[14] and Oliver et al.[15,16]

During the passage of the frontal band across PS 3 the precipitation was quite extensive, as shown by the series of radar echoes.

The sequence shows two bands of echo northwest of the ship at 0002. Behind these two bands there is a widespread echo area with numerous narrow bands within it. The observer aboard PS 3 reported a frontal passage at 0350 apparently on the basis of a wind shift from south to northwest. The wind shift apparently occurred with the passage of the very narrow band of echo that is best seen just northwest of the ship at 0208. The radarscope settings at 1028 and 1300 are not adequate to portray the extensiveness of the echo. The photographs do, however, show the rear edge of the echo area approaching the ship from the northwest. By 1810 the last vestige of the frontal band has practically disappeared to the southeast and a few scattered showers are visible to the north.

Surface observations of precipitation during the period are limited to those accompanying six-hourly synoptic reports, but these indicate light continuous rain occurring at 0600 and continuing through 1200, but ending before 1800.

Surface cloud observations were as follows:

0600	10 Sc 25		
1200	10 Sc 25		
1800	2 Cf 20	4 Ac 80	1 As 100
0000	1 Cu 20	1 Ac 80	1 Ci/

These observations show the clearing behind the frontal band and the relative absence of clouds in the area that is nearly clear in the cloud photograph.

There was no sounding at PS 3 at 1200. The sounding at 0000 on the 26th shows a steep lapse rate near the surface and variations in moisture throughout the sounding. Three levels show dew-point depressions small enough to suggest the possible existence of clouds. These levels are just below 900 mb, around 700 mb, and at about 550 mb.

At PS 5, radarscope settings were quite variable on the 25th, so the complete history of the approach of the frontal band was not recorded. A radarscope photograph at 0644 shows an increase in the shower activity that had been present since the previous day and also an elongated echo 125 miles northwest. This distant echo gradually spread across the scope, being detected from the center out to 150 nautical miles. Surface cloud observations during the period of extensive echoes were as follows:

1200	4 Sc 20 5 Cs/	2100	10 St 25
1500	10 Sc 25	0000	10 Sc 25
1800	10 Sc 25	0300	10 Sc 25

The only reported precipitation during the 25th and 26th was light drizzle at 2100 on the 25th, and then heavy, continuous rain from 0400 to 0710 followed by moderate rain until 1650 on the 26th.

A sounding at PS 5 at 1200 on the 25th shows a moist layer from the surface to the 820-mb level (about 5500 feet), and then an inversion with a dry layer up to the 640-mb level (about 12,000 feet). Above the 640-mb level the sounding is moist with dew-point depressions of only two or three degrees up to the 400-mb level, above which moisture values are no longer given. The reported clouds at this time were stratocumulus with bases at 2000 feet and a layer of cirrostratus. The tops of the stratocumulus are probably at 5500 feet; the deck is 3500 feet thick. The cirrostratus would be in the moist layer above 12,000 feet.

The sounding at 0000 on the 26th shows a slightly shallower moist layer at the surface, the top now being located at the 870-mb level, or 4000 feet. The dry layer above the lower moist layer is also shallower, extending only to the 730-mb level (about 9000 feet). The sounding is then moist up to the 400-mb level. At the time of this sounding the observer saw ten-tenths stratocumulus at 2500 feet. These were probably 1500 feet thick, extending up to the 870-mb level. Above 9000 feet there were probably other clouds obscured from the surface observer's view. The echoes at the time of this sounding are extensive out to 100 miles, with some echo visible to 140 miles to the northeast. At 140 miles the base of the radar beam is 12,000 feet above the surface while the top is at 21,500 feet; therefore, there must be dense cloud or precipitation within this altitude interval. In this case precipitation may extend to considerable heights since the level at which snow melts to rain (zero-degree isotherm) is at the 750-mb level, or 8000 feet. The base of the radar beam does not rise above this level until a point 110 miles from the station. Thus, the echo is probably from extensive rain within the well-defined cloud bands evident to the northwest of PS 5 in the satellite photographs. As mentioned earlier, heavy rain was reported at the ship after 0400.

Back in the cold air, well to the north of the front, there are cellular clouds in the vicinity of PS 1. A radar photograph at 2044 shows the distribution of radar-detected precipitation within these cellular clouds. Cloud observations at 1800 and 0000 reported the cloud cover as four-tenths cumulonimbus and five-tenths towering cumulus, respectively. Further precipitation was reported a number of times between 1200 on the 25th and 0100 on the 26th. The type of precipitation and the time it began (the time it stopped is unknown) was:

Type	Time Began
Hail pellets	1204
Moderate snow shower	1207
Hail pellets	1329
Moderate snow shower	1705
Moderate snow shower	1801
Light snow shower	0004
Hail pellets	0056

These observations attest to the convective nature of the cloud cover, and the frequent observations would indicate a probable short duration of precipitation from the individual small cells as they moved over the ship. A sounding taken at 0000 shows a very unstable lapse rate and considerable moisture up to the 700-mb level. Above this level moisture decreases, becoming unmeasurable above the 675-mb level (about 11,000 feet). The maximum range to which the showers are detected is 60 miles. The top of the radar beam at this distance is 6000 feet. There may be showers extending above this level, but at 60 miles the width of the radar beam may be so great that the small showers do not fill enough of the beam to return a detectable signal to the radar. This consideration together with the sounding makes it reasonable to assume that these clouds may extend to around 10,000 feet and are packed with snow and hail pellets.

h. 26 February

Some of the most interesting echo activity of the entire period occurred during the interval between satellite passage on the 25th and 26th. The sequence of radarscope photographs from PS 3 in Fig. B-8 shows the echo pattern between 0603 and 1707 on the 26th. At 0603 there are two short bands of echo located 50 and 100 miles west of the ship. There is also a faint band of echo 100 miles to the southeast of the ship. These areas of echo increase during the next two hours, resulting in a northeast-southwest band 75 to 100 miles southeast and a double northwest-southeast band between 25 and 60 miles to the west. At 0936 there are a number of showers between the two bands. These showers increase in size and merge into the northeast-southwest band. Additional areas of showers then develop near the center and form into a new northeast-southwest band by 1607. After 1607, the northwest-southeast band to the southwest dissipated and the band to the east moved eastward beyond range of detection. The determination of the relative motions of the echoes composing these various areas of echoes was difficult because in this case the echo motion was slow compared to the speed of the ship, and changes in ship heading resulted in motions with respect to the scope center that could not be translated into echo motions with respect to a point on the earth. Without changes in the shape and area of the echo areas it would be possible to subtract the ship's motion from the relative echo motions to obtain the true motion, but such changes were constantly taking place even though the general configuration persisted for a few hours. The configuration of two bands almost at right angles to each other is most pronounced on the radar photographs at 0734 and 0835. This is nearly halfway between available satellite photographs, so there is no cloud cover to use in interpreting the configuration. Examination of the two sets of satellite photographs (Figs. B-7 and B-8) shows that the sharp trailing edge of the frontal band remained aligned in a northeast-southwest position while moving from the vicinity of PS 3 to 50°N, 130°W. Six-hourly surface maps show that the low center and associated warm front were moving toward the northeast. At satellite time on the 25th the low apparently was located somewhere southwest of 40°N, 140°W, and the two north-south cloud bands, one along 135°W (near 35°N) and the other along 140°W, were destined to consolidate in the next 24 hours to form the cold-frontal cloud band. These cloud bands apparently contain the northwest-southeast bands of radar echo that are just west of PS 3 during the period. The southwest-northeast bands mainly southeast of the station are a part of the frontal cloud band extending northeastward from the low center. Why these bands do not conform to the satellite-viewed cloud cover of the frontal structure near the low center would be an interesting subject to study. Also of interest is what happened to the spiral cloud pattern defining the PVA MAX. If any of this cloud cover passed across PS 3 its passage was apparently so rapid that it did not result in an overcast at any of the six-hourly cloud observations on the 26th. In accordance with the findings of Bittner it seems likely that it moved eastward, its center of circulation passing well north of PS 3, and produced deepening of the low cell which is located south of 35°N on the 0000 26 February surface map.

A sounding at PS 3 at 1200 on the 26th shows a saturated layer up to the 850-mb level, and then a generally dry condition except from the 620-mb level to the 530-mb level. A cloud observation at the time of this sounding indicates three-tenths of stratocumulus with bases at 2500 feet, showing that the ship was still in a position northwest of the frontal cloud band as it had been at the time of the satellite photograph on the 25th. At 1800 the cloud cover was two-tenths of cumulus with bases at 2000 feet, and two-tenths of altocumulus with bases at 8000 feet, so the frontal band apparently still was not close to the ship. At 0000 on the 27th there was five-tenths cumulus with bases at 2000 feet and two-tenths cirrus at an unknown altitude. A sounding at this time shows relatively little moisture except at the base of the inversion at the 880-mb level. No precipitation was reported at any time on the 26th.

The satellite photograph at 2146 on the 26th shows the frontal band just west of Klamath. The radar at that station (K) showed a band of echo detected to 150 miles and extending in a southwest-northeast direction across the western half of the PPI. A sounding at Medford, Oregon, shows a steep lapse rate with no major inversions below the tropopause. The sounding is quite warm and except for a layer between about the 700 and 550-mb levels, generally dry. Winds on the sounding are from a westerly direction with speeds in excess of 50 knots from the 700-mb to the 150-mb level.

On the 27th, there were numerous small shower-type echoes in the vicinity of PS 3. Figure B-9 shows PPI photographs of these showers from 0210 to 0858. This sequence shows first a band of showers west of the station, then an area of showers surrounding the station, and then a semblance of a band as the showers moved eastward. The cloud observations at 0600 and 1200 were

0600	5 Sc 20	
1200	6 Sc 20	8 Ci/

In addition, at 0600 the report indicated light intermittent rain, and rain during the previous six hours. At 1200 there was a light rain shower and rain showers reported during the previous six hours. This would indicate PS 3 was in the cellular cloud cover shown west and southwest of the ship in the satellite photograph on the 26th. A sounding at 1200 shows near saturation to the 800-mb level, and then an inversion and a marked decrease in moisture above the 750-mb level (about 8000 feet). In this case apparently the temperature is warm enough so that the showers are rain only and not snow and hail pellets as at PS 1 on the 25th.

4. Summary of Case History

During the period studied, several migratory pressure systems moved across the radar network. Surface observations and radiosondes (plotted as time sections from copies of the ship's weather records) on Fig. B-10 show variations in surface weather and upper air temperatures as the migratory pressure systems and fronts moved over the line of Picket Ships. The major features shown by the data for PS 1 are the frontal passage between 0600 and 1200 on the 21st that is subsequently followed by a decrease in moisture between the 580- and 700-mb levels. Later in the period--i.e., from 1800 on the 23rd to 1200 on the 24th--there is light continuous rain and the soundings show near saturation to about the 400-mb level. After a cold-frontal passage just prior to 1200 on the 25th, cumulonimbus clouds and rain showers occurred. Soundings during the period of convective clouds show steep lapse rates and a low tropopause (26,000 feet at 0000 on the 26th).

Data from PS 3 also show a frontal passage between 0600 and 1200 on the 21st. The prefrontal sounding shows a deep, moist layer (from which rain is falling). Again from 0000 on the 23rd to 0000 on the 25th there is considerable moisture to high levels and some precipitation, although the precipitation is not as continuous as it was at PS 1. On the 26th, the surface observations reflect the passage of a developing low-pressure center southeast of the station. The soundings at this time show no marked low-level inversion although there is a decrease in dew points at the 850-mb level.

The surface observations and soundings from PS 5 show the passage of a large, high-pressure area across the station during the period. There was a weak front (which passed PS 5 around 1200 on the 21st) preceding the high, and another, stronger front following the high-pressure area. The later front passed the station around 1200 on the 26th and was preceded by heavy rainfall.

One of the major features shown by the time section for PS 7 is the low-level inversion that was present during most of the period. There was little moisture above this inversion except at the start and end of the period. The cold front that passes PS 5 on the 26th, passed PS 7 shortly after 0000 on the 27th. The precipitation with (and ahead of) the front was the only precipitation observed during the period.

Personnel aboard the ship manning PS 9 during this period did not make many soundings because of other duties. Surface observations are not shown because after 1800 on the 26th, the ship was off station after this time. Available soundings show a cool, moist surface layer with very little moisture aloft except at 0000 on the 22nd. No precipitation was observed at this station during the period.

Cloud cover with these systems varied from practically no clouds near the centers of the anticyclones to extensive areas of multiple cloud decks accompanying the warm fronts of developing cyclones. When the configuration of the cloud cover made it apparent that the clouds were associated with a definite synoptic feature (e.g., cold front, warm front, low center) the appearance of the clouds generally provided clues as to the type and extensiveness of attendant precipitation. When the cloud cover was far removed from active fronts or low-pressure areas--e.g., extensive areas of stratus or cumulus--precipitation was less likely but still occurred, and the appearance of the cloud did not always indicate the extensiveness of the precipitation. Further, the presence or absence of radar-detectable precipitation falling from a deck of stratocumulus appeared to depend on the temperature at the cloud level, precipitation being more likely from the colder clouds. Therefore the latitude at which the cloud cover is located could be an additional factor to be considered where temperature varies with latitude.

During the period there were some marked changes in cloud configuration in the 24-hour interval between satellite passes that could not be interpreted even with intervening radar data. One example is the apparent merging of two fronts between the 20th and 21st and the resulting narrow frontal band. A second example is the development of the low-pressure area between the 25th and the 26th. Without knowledge of the rate at which such changes take place it is not possible to state how far in the future cloud-precipitation relationships deduced from a given cloud photograph can be extrapolated. Synchronous satellites will, hopefully, provide data on the rates of changes in cloud configuration.

APPENDIX C

NATURE OF RADAR PRECIPITATION ECHOES

APPENDIX C

NATURE OF RADAR PRECIPITATION ECHOES

The objective of the research presented in this report was the determination of the extensiveness of precipitation within various types of cloud cover. In this study, the extent of precipitation was to be measured by a network of radars. In order to assess the nature of the echo presented on the PPI scopes of the various radars it becomes necessary to examine the characteristics of the radars involved and to determine whether the photographed echo is truly precipitation or whether the radars are capable of detecting non-precipitating clouds to substantial ranges. In this study the majority of the radar data were collected by U.S. Navy Picket ships with SPS-8 radars and by USWB stations with WSR-57 radars. Although radar data were also collected by the Picket ships with other radars and by ADC sites with radars other than those mentioned above, this Appendix will be restricted to a discussion of the SPS-8 and the WSR-57. The SPS-8 is a height-finding radar, the primary mission of which is to determine the altitude of aircraft. A radar of this type characteristically has a beam that is narrower in the vertical than in the horizontal direction. With such a beam the volume of the atmosphere illuminated at any given range is confined to a relatively thin layer of the atmosphere. To make an assessment of the ability of this radar to detect meteorological targets one can make use of the radar equation in the form

$$\overline{P_r} = \frac{P_t G^2 \lambda^2 \theta \varphi h \eta}{512 \pi r^2} \qquad \text{(C-1)}$$

where

$\overline{P_r}$ = Average received power

P_t = Transmitted power

G = Antenna gain

λ = Wavelength

θ = Horizontal beamwidth

φ = Vertical beamwidth

h = Pulse length

η = Reflectivity per unit volume

r = Range.

When values of the various parameters for the SPS-8 radar are inserted in the equation in the appropriate units, the equation reduces to the following form:

$$\overline{P_r} = 10.7 \frac{\eta}{r^2} \quad . \tag{C-2}$$

Inserting a reasonable value for the minimum detectable value of $\overline{P_r}$ and converting to decibel notation we find

$$10 \log \eta = 20 \log r - 143.25 \quad . \tag{C-3}$$

This equation may be solved to determine the range (r) at which the reflectivity (η) associated with a given rainfall rate may be detected, or to find the maximum range at which a rainfall rate with a given reflectivity may be detected. Table C-1 lists reflectivities for several rainfall rates.

Table C-1

TYPICAL VALUES OF η FOR VARIOUS RAINFALL RATES

Reflectivity η(dBm^{-1})	Rainfall Rate R (mm hr^{-1})
-63	50
-68	25
-74.5	10
-75.5	5
-90.5	1
-108.0	0.1
-122.5	0.01

When a value for r of 100 miles is substituted in Eq. (C-3), the resulting value of 10 log η is -103.25. As Table C-1 shows, this corresponds to a rainfall rate slightly greater than 0.1 mm hr^{-1} (the exact value is 0.17 mm hr^{-1}). Thus the SPS-8 radar is capable of detecting very light rain at a range of 100 nautical miles.

Comparative figures for the WSR-57 radar can be determined. An equation similar to (C-3) but for the WSR-57 is either

$$10 \log \eta = 20 \log r - 169.2 \qquad \text{(C-4a)}$$

or

$$10 \log \eta = 20 \log r - 156.1 \quad . \qquad \text{(C-4b)}$$

The two sets of parameters that result in two equations are given by Senn and Hiser[17] and are based on (1) manufacturer specifications and (2) field performance or computed values. The rain rates that could be detected at 100 miles based on these two sets of data are given in Ref. 17 as 0.03 mm hr^{-1} for manufacturer's specifications and 0.08 mm hr^{-1} for the other set of values. Equations (C-4a) and (C-4b), which are uncorrected for attenuation, give values of less than 0.01 and 0.26. Part of this difference may also be due to differing assumptions in the reflectivity associated with various rainfall rates. Regardless of the exact value of the rainfall rate detectable by the WSR-57 at 100 miles, whether it is less than 0.01 or 0.08, this radar is apparently more sensitive than the SPS-8, since the latter could only theoretically detect 0.17 mm hr^{-1} at 100 miles. Given that both radars can detect very light rain at 100 miles, one must consider that rainfall rates as measured by rain gages are <u>surface</u> measurements and that the radar beam at 100 miles is well above the surface. Figure C-1 shows the height of the radar beam as a function of range. At 100 miles the center of the radar beams is in the vicinity of 10,000 feet. Since radar reflectivity of precipitation under standard atmospheric refractive conditions usually decreases with height, any values of reflectivity detectable at 100 miles should be considered less than the reflectivity at the surface at that distance. Thus, if the radar "sees" an echo at 100 miles or more the rain rate at the surface would normally be greater than that associated with the reflectivity used in the computation of minimum detectable rainfall rate.

There may be circumstances, however, under which the radar detects a precipitation echo and there is no surface rainfall. One such condition would be when any rainfall evaporated before it reached the surface. Another would be when the upward vertical motions within the clouds were sufficient to "store" or suspend precipitation particles so they could not immediately fall out of the cloud. Figure C-2 shows a radarscope photograph of echoes that appear to be returned from both precipitating clouds and non-precipitating clouds. Beneath the radarscope photograph and on the same scale, a diagram represents the position of the radar beam in the atmosphere. On the right half of the figure echoes terminate in a ring about 45 miles from the radar. At this distance the base of the radar beam* reaches the cloud base, so the lack of echoes closer to the radar must mean that there is no precipitation below the cloud base. To the left of the center there is echo out to about 40 miles from the center. This echo is close enough to the center so that the radar beam has not reached the reported cloud base; thus, this echo must be from rain falling out of the cloud (the observer aboard the ship reported rain beginning at the time the leading edge of this echo reached the ship).

At greater distances to the west the photograph shows shower-type echoes. These echoes are in the region above the cloud base, so they may be either local regions of denser cloud or precipitation. Examination of these echoes as they move closer to the radar would, in most instances, make it possible to determine whether the echoes were cloud

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*The beamwidth is taken to the half-power points so there is a possibility that some echo may be detected beyond the half-power points and even in side-lobes. The result of such detection would increase the areas of individual echoes but would not change the overall echo pattern.

or precipitation. If they remained essentially unchanged as they moved within the range where the beam was below the cloud base, they would be positively identified as precipitation. Thus, to determine whether a given echo is precipitation or cloud, it is necessary to consider the behavior of the echoes as they move by the radar station as well as the theoretical computations of rainfall rates detectable by the radars under consideration.

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13 ABSTRACT

Analyses of concurrent radar data and TIROS IX cloud photographs were made to develop techniques for determining areas of precipitation and severe weather within a given satellite observed cloud situation. During the four-month period studied (14 February to 15 June 1965) there were a number of occasions when frontal bands or cyclone centers were within range of one or more of the ten radar sites at the time of satellite passage. Examples of the precipitation distribution associated with various synoptic patterns are presented with discussions of pertinent features of the attendant cloud cover. From these examples a model of the probable distribution of precipitation within and around a typical maritime cyclone was constructed. The report also discusses situations in which there is widespread cloud cover but little or no precipitation. (

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14 KEY WORDS	LINK A		LINK B		LIN[K C]
	ROLE	WT	ROLE	WT	ROLE
Meteorological radar Meteorological satellites Cloud photographs Precipitation Maritime cyclones Convective showers Warm fronts Cold fronts					

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