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Satellite data that are currently available in numerical form for operational use include temperature profiles and cloud-motion measurements. In this study, several different techniques were tested for possible use in deriving wind profiles from these data. The eventual application of the wind profiles would be in objective analysis and numerical weather prediction. The techniques were tested using research data sets prepared by the National Environmental Satellite Service (NESS) at the University of Wisconsin. (Cont.)

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Block 20, Abstract, Continued

The satellite data consist of high-resolution TIROS-N temperature profiles and and GOES cloud-motion measurements. The evaluation of the techniques was based on comparisons with radiosonde observations over the United States.

Two of the techniques tested were found to give promising results: one, a technique based on the use of thermal winds to extrapolate wind values upward and downward from the cloud-motion level, and the other a technique based on eigenvector calculations. These two techniques, or similar ones, should be of current operational value over oceanic areas devoid of conventional data, provided that reliable height values for cloud motions and reasonably accurate estimates of surface winds can be provided.

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AB (27) Satellite data that are currently available in numerical form for operational use include temperature profiles and cloud-motion measurements. In this study, several different techniques were tested for possible use in deriving wind profiles from these data. The eventual application of the wind profiles would be in objective analysis and numerical weather prediction. The techniques were tested using research data sets prepared by the National Environmental Satellite Service (NESS) at the University of Wisconsin. The satellite data consist of high-resolution TIROS-N temperature profiles and GOES cloud-motion measurements. The evaluation of the techniques was based on comparisons with radiosonde observations over the United States. Two of the techniques tested were found to give promising results: one, a technique based on the use of thermal winds to extrapolate wind values upward and downward from the cloud-motion level, and the other a technique based on eigenvector calculations. These two techniques, or similar ones, should be of current operational value over oceanic areas devoid of conventional data, provided that reliable height values for cloud motions and reasonably accurate estimates of surface winds can be provided. (Author)
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Enclosure (1) describes an automatic cloud tracking system based on the computation of the cross-covariance between satellite images, and gives examples of this system's application.

Enclosure (2) presents the results of a study to investigate techniques of deriving wind profiles from cloud motion vectors and satellite temperature soundings; a selected number of techniques are tested and compared.

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SATELLITE WIND-PROFILE TECHNIQUES

Prepared By:

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Contract No. N00228-79-C-K890

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NAVAL ENVIRONMENTAL PREDICTION RESEARCH FACILITY
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I INTRODUCTION

Meteorological satellite systems are now supplying large amounts of valuable data that were previously unattainable. The temperature profile data from the recent TIROS-N cover the globe and provide reasonably accurate descriptions of large-scale temperature structure (Smith et al, 1979).* Despite some remaining undesirable characteristics, these data are being used by the National Meteorological Center (NMC) to fill-in oceanic data-sparse areas (Phillips et al., 1979). Numerous studies have shown that cloud-motion measurements are valid if the cloud heights are known with reasonable accuracy (e.g., Hasler et al., 1979), which can be achieved using infrared observations. Improved sensors and processing procedures will permit more accurate depictions in the future, particularly of small-scale phenomena. Other types of meteorological data that may become available routinely from satellites include measurements of surface winds over the oceans (from microwave instruments like those used on SEASAT) and constant-level balloon observations of high-altitude conditions.

The various types of satellite data currently available do not in themselves give a complete description of the air flow of the atmosphere. However, they provide sufficient information for estimating wind profiles, the most obvious method being to use thermal winds derived from the satellite temperature profiles to build upward or downward from known wind values. The known wind values can be radiosonde winds, cloud-motion measurements, aircraft measurements, surface data, or some combination of these.

In this study by SRI International (SRI) for the Naval Environmental Prediction Research Facility (NEPRF), four different techniques were tested for deriving wind profiles from satellite cloud-motion measurements and retrieved temperature profiles. The testing was done using recent satellite data for 1979: The temperature retrievals were from the TIROS-N polar orbiting satellite, and the cloud motions were derived from GOES geosynchronous satellite imagery. The temperature profiles and cloud motions, which are of relatively high-spatial resolution, were provided by the National Environmental Satellite Service (NESS) at the Space Science Center, University of Wisconsin.

In Section II of this report, we describe the approach and the four different techniques that were tested. Section III gives a description of the data sources that were used, and presents computer flow charts that

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*References are provided in full at the end of this report.

pertain both to the data processing and the testing of the techniques. In Section IV, the results for the three test cases are presented, and a discussion is given of the errors, particularly the inaccuracies in cloud-height estimates and their effects on the results. Section V provides a summary with concluding remarks. Appendix A is included as a comparison between analyses of conventional radiosonde observations and of Atmospheric Variability Experiment (AVE) data.

II BASIC PROCEDURE AND TECHNIQUES

In collaboration with NEPRF personnel, four different techniques were selected for determining wind profiles from satellite data. The basic approach adopted for applying and testing the techniques was as follows:

- Step 1: Make horizontal grid-point analyses of temperature from the satellite data at the levels 850-, 700-, 500-, 400-, 300-, 250-, and 200 mb, and then calculate thermal winds. This produces a set of temperature and thermal-wind profiles at each vertical column of the three-dimensional mesh. [Thermal winds could also be derived directly from the radiance data--see Fleming (1979).]

- Step 2: Use the thermal-wind vectors at grid points to build geostrophic wind profiles upward from some given low-level wind. In this study, gradient-wind profiles computed in this manner were provided by NESS for the same locations as the temperature-profile data. (The gradient wind is similar to the geostrophic wind, but has curvature corrections for speed.) Thus, it was only necessary to analyze grid-point values of these gradient winds in conjunction with the temperature-profile values.

- Step 3: Construct an improved wind field at a selected level by analyzing the available cloud-motion data at this level using the gradient wind as a first guess. In this study, the 300-mb level was selected because the cloud-motion data for the test cases were principally at this level.

- Step 4: Apply one of the techniques to obtain improved wind fields at all the other levels, and thus improve the wind profiles at each horizontal location of the vertical columns of the mesh.

The wind-profile techniques that were tested in this study are described below.

Technique T1--In this technique, after cloud motions are analyzed for a selected height (h), a complete wind profile is derived for each grid point using a procedure based on a characteristic profile concept, which is as follows:

- The analyzed cloud motions provide the winds at the height h.
- The thermal-wind profiles, which are derived from the satellite temperature-profile data, are used to determine the height at which the thermal wind reverses direction--this is assumed to be the height of the maximum wind level (MWL). A reversal in thermal

wind is defined to take place at a certain height if the dot product of the thermal-wind vector below and above this height has a large negative value. Above 500 mb, the level having the largest negative dot product is assumed to be the MWL.

The wind-speed profile is then built upward and downward from the cloud-motion level (h) using relationships between speed and shear that were developed by Endlich and McLean (1960). At the MWL, the direction of the shear reverses. Wind directions are held constant with height.

Technique T2--In this technique, the improved wind analysis at the cloud-motion height (h) is first made nondivergent using the wind-altering method developed by Endlich (1967). In this method, the grid-point winds are altered in a systematic manner until the divergence of the wind field has been eliminated without changing the rotational properties of the flow. Based on previous studies (Viezee et al., 1972; 1977), eliminating divergence appears to be desirable because it eliminates a large part of the random measurement error. After the wind field at height h is made nondivergent, the satellite thermal-wind fields are used to directly extrapolate wind values both upward and downward to produce improved wind profiles at each vertical column of the three-dimensional mesh. If there were no cloud motions at height h in the vicinity of the location of a vertical column of the mesh, then the wind profile calculated for that location would essentially be the same as the original gradient wind profile.

Technique T3--This technique is a modification of T2; the modification is intended to account for the differences between geostrophic and nondivergent winds, as expressed by the balance equation. These differences can be as large as 10 to 20 percent of the geostrophic speeds in high-speed curved flow such as jet streams. In moderate or weak flow, the differences may be small and difficult to detect. Unfortunately, the wind speeds in the cases available for this study were mostly weak or moderate. The T3 technique operates as follows: After an improved wind field is analyzed at the cloud-motion height h and is made nondivergent as in T2, it is converted to a geostrophic-wind field, using the wind-altering technique applied to the balance equation; that is

$$f\zeta_g - \beta u_g = f\zeta - \beta u + 2J(u,v) \tag{1}$$

where u and v are the wind components, f is the Coriolis parameter, $\beta = \partial f/\partial y$, ζ is the relative vorticity, $J(u,v) = (\partial u/\partial x)(\partial v/\partial y) - (\partial u/\partial y)(\partial v/\partial x)$, and the subscript g denotes geostrophic values.

The right-hand side of the equation is calculated only once and held fixed, while the u_g and v_g values on the left side are successively altered until they satisfy Equation (1) and

$$\partial u_g/\partial x + \partial v_g/\partial y = -(\beta/f)v_g \tag{2}$$

After this computation is made, the satellite thermal winds are used to extrapolate geostrophic winds vertically. The geostrophic wind fields at each level are then converted to nondivergent winds, again using the wind-altering technique applied to the balance equation [Eq. (1)] in a reverse direction. This procedure is analogous to the standard solution of the balance equation that begins with height values at grid points and obtains a stream function. The above two applications of the wind-altering method are described in detail in literature (Endlich, 1968; 1970). The resulting nondivergent winds should be a better approximation to the real winds than the geostrophic winds in regions of strong winds.

Technique T4--This technique follows the approach described by Kalb (1979), which is based on calculating eigenvectors for the satellite geostrophic- (or gradient-) wind profiles. Only the first eigenvector for a profile is used, since it explains most of the variance of the profile, and a cloud-motion wind is used to estimate the coefficient of this first eigenvector. Since the coefficient applys at all levels, it is in turn used with the first eigenvector to compute the entire wind profile. A more detailed explanation follows.

By the use of linear transformations based on the eigenvectors of the covariance matrix, the number of variables can be reduced while still retaining most of the information in the original data set. Lorenz (1956) has given a description of the method as applied to temperature and pressure observations; others, such as Holmström (1963), have used the eigenvector method for representing wind profiles.

A profile of any scalar quantity can be represented as a linear combination of a set or orthonormal eigenvectors, and the value of q for any profile (n) and for any level (ℓ) would be given by:

$$q(n,\ell) = \overline{q(\ell)} + \sum_{k=1}^{K} \left[c(n,k) \cdot e(\ell,k)\right] \qquad (3)$$

where $\overline{q(\ell)}$ is the average value of q at the ℓ^{th} level, i.e., $\sum_{n=1}^{N} q(n,\ell)/N$

c(n,k) is the coefficient associated with n^{th} profile and k^{th} eigenvector element (independent of the level).

$e(\ell,k)$ is the element for the ℓ^{th} level of the k^{th} eigenvector; thus, the k = 1 column of elements $[e(1,1), e(2,1), \ldots e(\ell,1)]$ is the first eigenvector.

K is the total number of eigenvectors, which is equal to the total number of levels (L).

N is the total number of profiles (in our application, the total number of vertical columns in the mesh that are used in the evaluation).

The coefficients c(n,k) are inner products of the input data vector and the eigenvector, and can be calculated by:

$$c(n,k) = \sum_{\ell=1}^{L} \left[q(n,\ell) \cdot \overline{q(\ell)}\right] \quad e(\ell,k) \qquad (4)$$

The normal procedure would thus consist of calculating first the eigenvector* and then the coefficients of the original data set. One thus replaces the NxL observations with L^2 eigenvector elements and NxL coefficients. The principal value of this procedure is that the first eigenvector explains most of the variance, and each additional eigenvector explains a successively smaller part of the remaining variance. If all the eigenvectors are used, the profile is reconstructed exactly. Kalb (1979) found in his study that the first eigenvector explains over 80 percent of either the u or v wind-profile variance.

In Kalb's application, the u and v wind components are treated independently and each has its own set of eigenvectors. The u_g component of the geostrophic (or gradient) wind is first used in place of q in Eq. (3) to calculate a set of eigenvectors. An estimate of the $c(n,\ell)$ values are then obtained from the cloud motion u values at the cloud level, say $\ell = 5$, by:

$$c(n,1) \approx \left[u(n,5) - \overline{u_g(5)}\right]/e(5,1) \qquad (4)$$

Estimates of the u wind component at all levels are then made by:

$$u(n,\ell) \approx \overline{u_g(\ell)} + c(n,1)\cdot e(\ell,1) \qquad (5)$$

The v component profiles, $v(n,\ell)$, are then calculated similarly. [The u and v components can also be calculated simultaneously as done by Ludwig and Byrd (1980), which would be more efficient.]

---

*Determining the eigenvector matrix E is a standard problem. It first requires determining the covariance matrix A of the data set, which is defined as:

$$A = QQ^T$$

In this application, the matrix Q would be an LxN matrix, where L is the number of levels and N is the number of gradient-wind profiles. Each element in Q is the difference between the actual data $q(n,\ell)$ value and the mean for the level over all N profiles $\left[\overline{q(\ell)}\right]$. The matrix Q^T is the NxL transpose of Q. The eigenvector matrix E is defined as the matrix that satsifies:

$$EE^T = I \text{ and } EAE^T = D$$

where I is the identity matrix and D is the diagonal matrix of eigenvalues. In this application, the International Mathematical and Statistical Library (IMSL) subroutines BECOVN and EIGRS were used. BECOVN is also used to evaluate the mean u_g and v_g values for each level.

In summary, the satellite gradient-wind data are first used to calculate a set of eigenvectors (one for each layer) for both the u and v components. The cloud-motion winds are then used to estimate the coefficients that are used with the first eigenvectors of both the u and v wind-components profiles. Since these coefficients also apply at each level with different elements of the first eigenvector, and since the first eigenvector explains most of the variation in the wind profile, it is possible to estimate u and v wind components at all levels. If more than one cloud-motion (or other wind) measurement is available, a more accurate estimate can be made by using the first and the second eigenvectors.

It should be noted that this technique is based on the use of an initial gradient-wind profile that is built upward from given surface winds, and that these initial profiles play a significant role, since they are used for calculating the eigenvectors and the $\overline{u_g}$ and $\overline{v_g}$ values used in Eq. (4) and (5).

III TEST CASE SELECTION AND COMPUTER FLOW CHARTS

The three test cases that were selected are special satellite data sets that were provided by NESS. These data sets contain TIROS-N temperature-profile data and cloud-motion measurements based on GOES cloud imagery. The temperature-profile data were processed using the McIDAS interactive system at the University of Wisconsin. This type of processing permits the generation of a dense network of soundings (Smith et al., 1979). The cloud-motion measurements were also made with the McIDAS system (Smith, 1975). The accuracies of the cloud-motion measurements are quite good; Wilson and Houghton (1979) estimate the error to be $\sim 4.7\ ms^{-1}$. However, the estimation of the cloud heights are based on simplified emissivity assumptions and the use of standard atmospheric values (Mosher, 1976). The data sets also contain gradient-wind profiles; gradient or geostrophic wind profiles are calculated with the McIDAS system from pressure values built-up from the surface (see Kalb, 1979).

The three test cases are for 10 April, 14 March, and 2 May 1979, and the regions covered in these test cases are shown in Figure 1. All three cases are over the United States, where there are ample conventional radiosonde data to use in judging the techniques: the first two cases (10 April, 14 March) are over the central-eastern United States, and the third case (2 May) is over the western United States. All of the cases occurred during the spring of 1979, but are distinctly different. The 14 March case contains a jet stream over the northeastern United States, and the 10 April case involved an intense squall-line situation.

Conventional U.S. radiosonde data for these test cases were obtained from the National Climatic Center (NCC) for use as ground-truth data. Also, Atmospheric Variability Experiment (AVE) three-hourly radiosonde data were obtained from the National Aeronautics and Space Administration (NASA)* for the 10 April case.

The flowcharts for computer software used in this study are shown in Figures 2 and 3. The conventional radiosonde data are analyzed using the AEROMAT program (Figure 2) that was previously developed at SRI (Mancuso and Endlich, 1979; Jones and Mancuso, 1979). Programs were also developed for processing the NESS satellite data (Figure 3): the processing consists of decoding and selecting the data for use in testing and evaluating the four candidate techniques for estimating wind profiles from satellite data. The main testing program, TESTECH (Figure 3), is used to test the various techniques by successively replacing the subroutine that implements each of the techniques. The VALDAT (Figure 3) program provides quantitative comparisons of the technique's results with the radiosonde winds.

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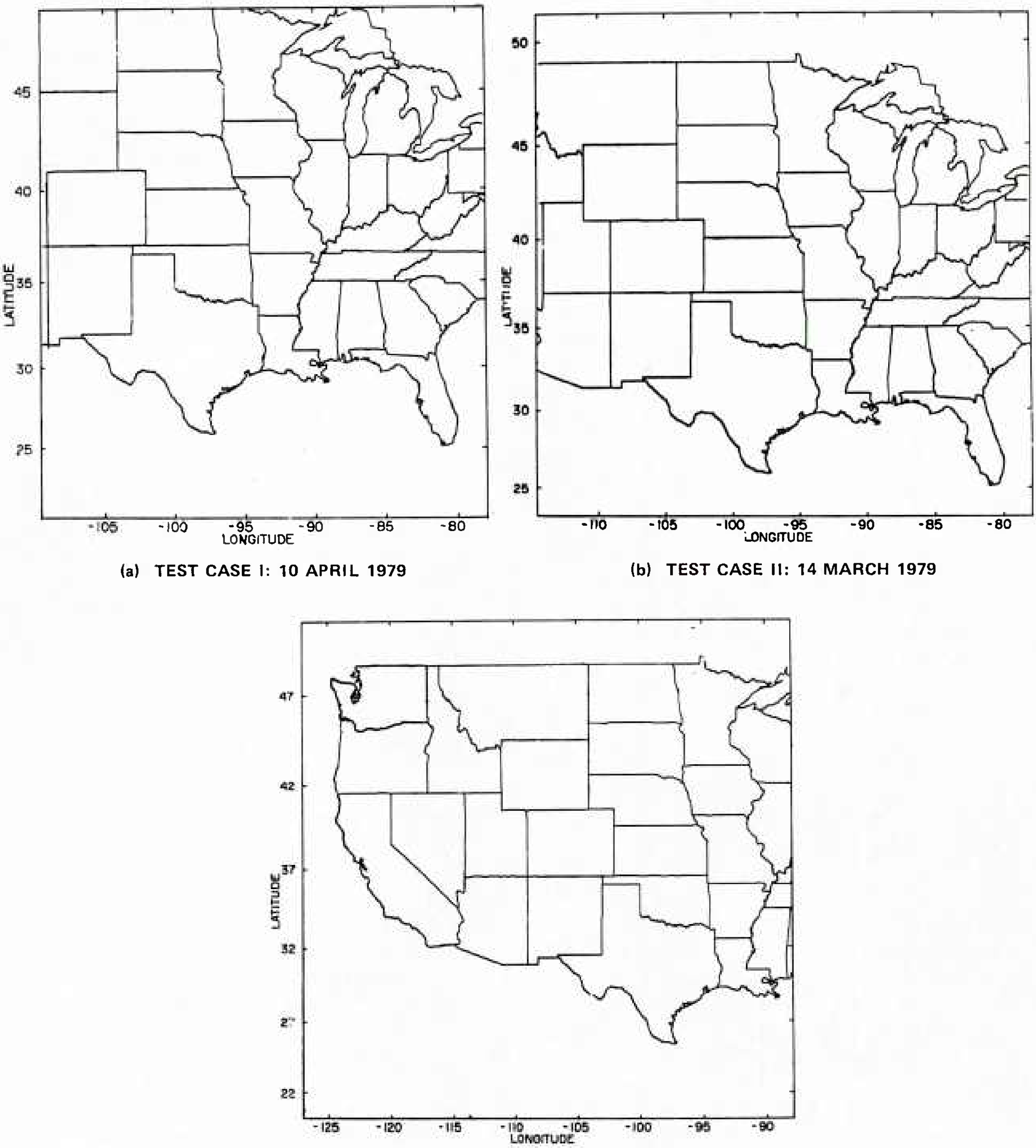
*These data were made available to SRI by the NASA Marshall Space Flight Center.



(a) TEST CASE I: 10 APRIL 1979

(b) TEST CASE II: 14 MARCH 1979

(c) TEST CASE III: 2 MAY 1979

FIGURE 1 REGIONS COVERED BY THE THREE TEST CASES USED IN THE STUDY

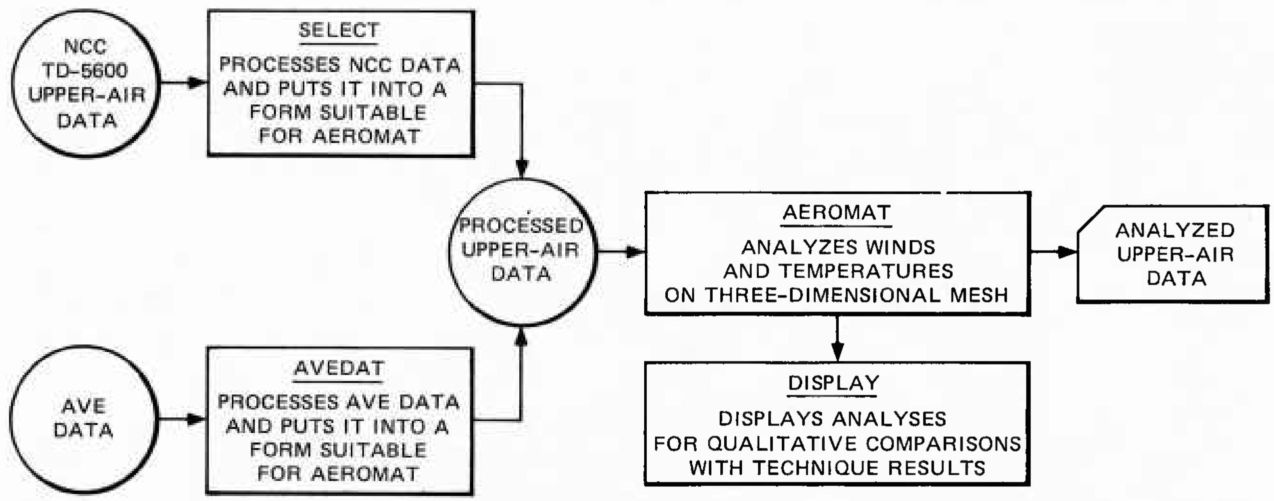


FIGURE 2 PROCESSING AND ANALYSIS OF UPPER-AIR RADIOSONDE DATA USING SRI PROGRAM AEROMAT

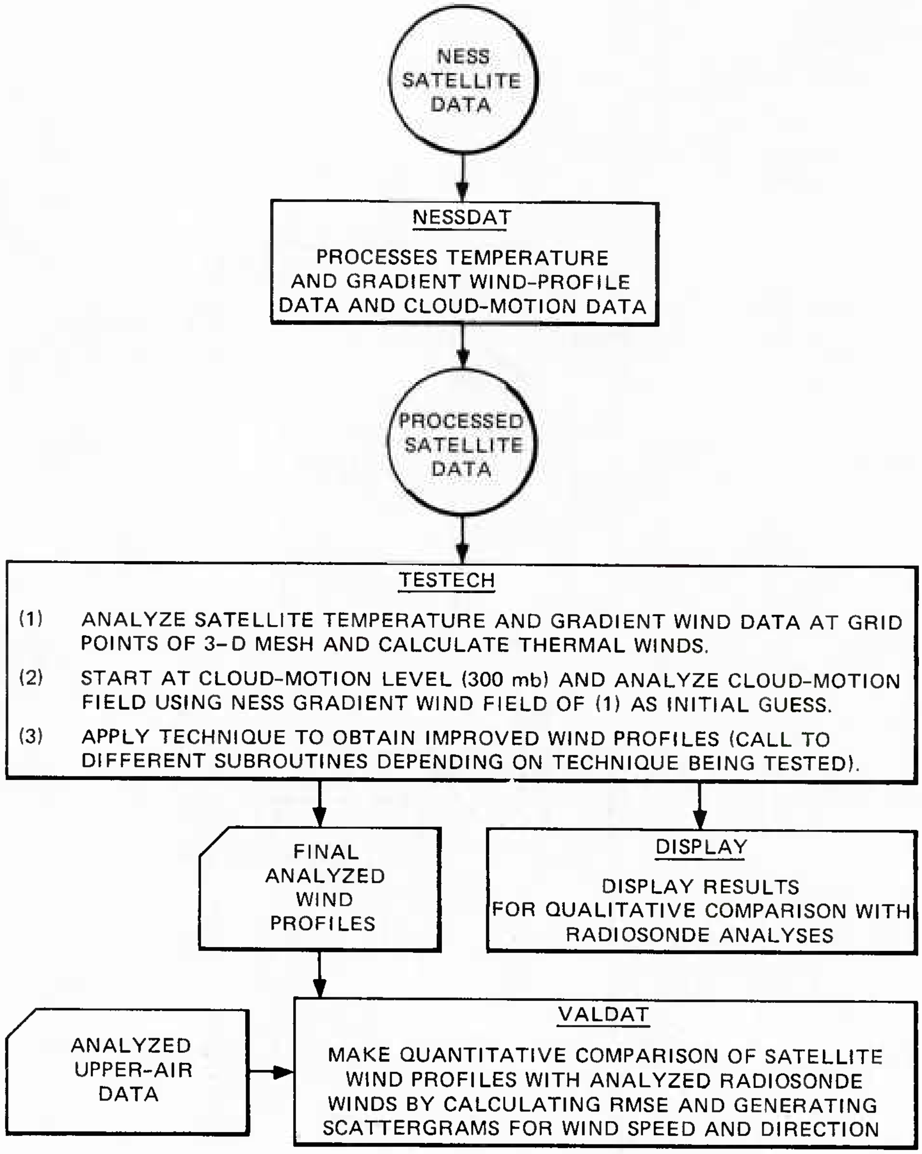


FIGURE 3 FLOW DIAGRAM SHOWING PROCESSING OF NESS DATA AND WIND-PROFILE TECHNIQUE TESTING AND EVALUATION

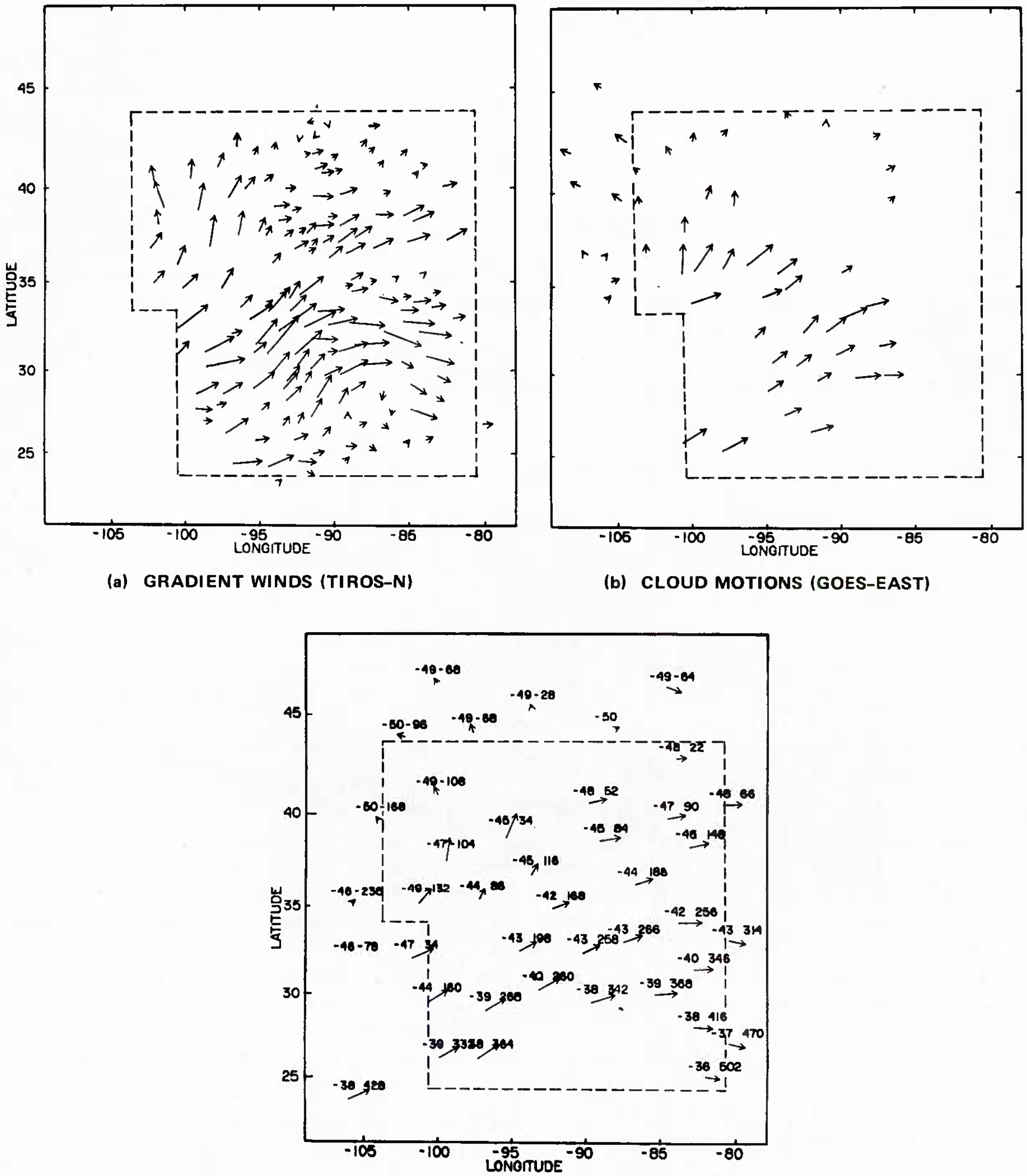
IV RESULTS

A. Test Case 1: 10 April 1979

Figure 4 shows the gradient winds, cloud motions, and radiosonde data at the 300-mb level for the 10 April 1979 case. The gradient-wind and cloud-motion data do not completely cover the analysis region, but show considerable overlap. The conventional radiosonde data provide a relatively complete and reasonably dense coverage, although they are for 0000 GMT 11 April, four hours after the satellite data time (2000 GMT 10 April). The area enclosed by dashed lines shows a subregion that contains a complete coverage of both the gradient-wind and radiosonde data, and that was used for evaluating the results (it was not made a requirement that this subregion contain cloud-motion data). In this test case, the gradient winds show a number of inconsistencies, such as at 89°W and 35°N. Ideally, these data should be edited; however we believed that this would introduce a personal bias into the results of the study.

Figure 5 shows grid-point analyses of the three data sets of Figure 1. The gradient-wind analysis [Figure 5(a)] was used as a first guess for the cloud-motion analysis [Figure 5(b)]. Figure 5(c) is a time interpolation for 2000 GMT made from three separate analyses of radiosonde data at 1200 GMT 10 April, 0000 GMT 11 April, and 1200 GMT 11 April. The interpolated analyses give reasonably good results, as shown by comparisons with AVE data that were available for the 2000 GMT 10 April 1979 (see Appendix). The grid-point analysis of the gradient wind shows features that differ considerably in detail from the radiosonde analysis, partially due to the use of unedited gradient winds. The cloud-motion analysis [Figure 5(b)] also shows a somewhat different pattern than the radiosonde wind analysis [Figure 5(c)]. For reasons given later, it appears that this is mainly caused by inaccuracies in cloud-height determination and the assignment of the cloud motions to unrepresentative pressure levels.

The TIROS-N temperature and thermal-wind analysis for the 300-mb level at 2000 GMT 10 April, shown in Figure 6(a), are based on temperature data given at the same locations as those shown for the gradient winds of Figure 4(a). The temperature and thermal-wind analysis, which as based on the radiosonde data for the same level and time, is shown in Figure 6(b). (This result was also interpolated from three separate analyses of radiosonde data at the times 1200 GMT 10 April, 0000 GMT 11 April, and 1200 GMT 11 April 1979). The 300-mb patterns of both types of data are similar; however, they differ in detail as shown by the thermal-wind vectors, and the radiosonde temperature are about 2° colder. Differences between these two types of data should be expected since one (radiosonde) is a point measurement, while the other (satellite) represents a volume measurement.



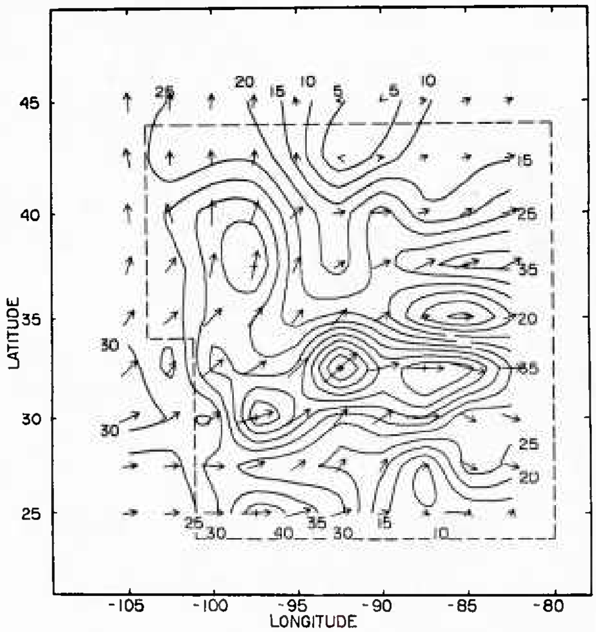
(a) GRADIENT WINDS (TIROS-N)

(b) CLOUD MOTIONS (GOES-EAST)

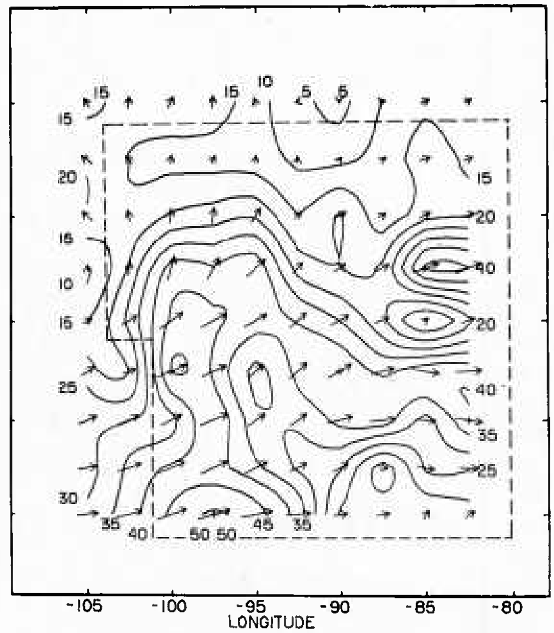
(c) RADIOSONDE DATA (0000 GMT 11 APRIL)

FIGURE 4 AVAILABLE DATA FOR THE 300-mb LEVEL OF TEST CASE I, 2000 GMT 10 APRIL 1979

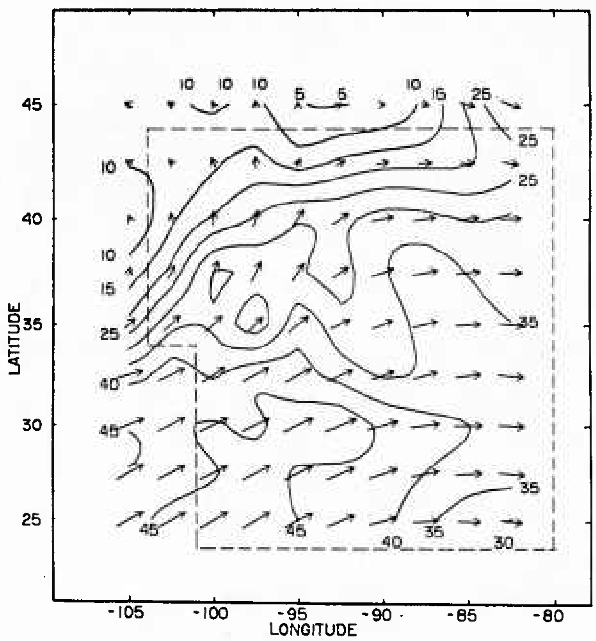
Satellite gradient-wind and cloud-motion data provided by NESS.



(a) **GRADIENT WINDS**



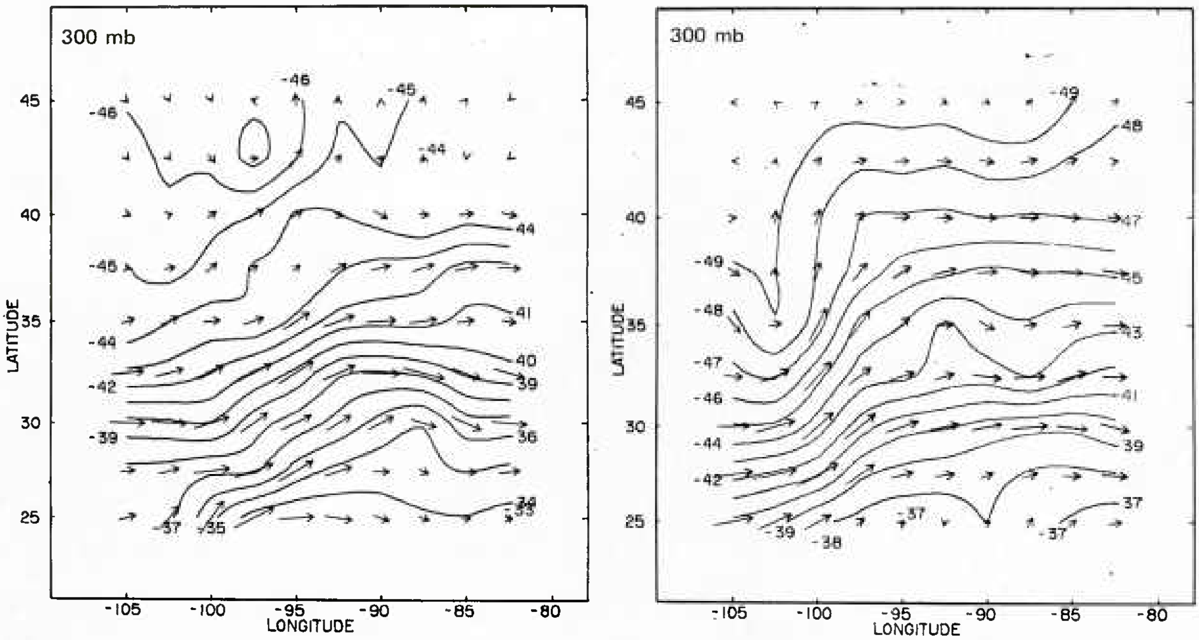
(b) **CLOUD MOTIONS AND GRADIENT WINDS**



(c) **RADIOSONDE WINDS**

FIGURE 5 GRID-POINT ANALYSES FOR THE 300-mb LEVEL OF TEST CASE I, 2000 GMT 10 APRIL 1979

Wind speeds shown by isotachs in ms^{-1}.



(a) BASED ON TIROS-N DATA

(b) BASED ON RADIOSONDE DATA

FIGURE 6 TEMPERATURE (°C) AND THERMAL-WIND ANALYSES FOR 2000 GMT 10 APRIL 1979

Figure 7 shows the GOES-EAST satellite infrared (IR) image for 2000 GMT 10 April 1979. It reveals a deep, low-pressure system over the southwestern U.S. and an associated high-cloud mass lying to the east, over northwestern Texas and southern Oklahoma. This weather system, which produced numerous tornadoes at this time along the Texas/Oklahoma border, is discussed in detail by Williams et al. (1980). The image also shows a typical jet extending along the Gulf coast. Generally, high clouds (brightest areas) exist in all areas where 300-mb cloud motions are shown in Figure 4(b). There is a cluster of high clouds over the eastern Kentucky/Tennessee area; however, for this case there were no cloud-motions measurements made east of 85°W longitude. The clear area extending from southeastern Missouri to Georgia is also the area where weak gradient-wind speeds are shown in Figure 4(a). These weak gradient-wind speeds do not appear to be very consistent with either the cloud motions or radiosonde winds.

The 850-, 500-, 300- and 200-mb wind analyses for 2000 GMT 10 April 1979 that were based on radiosonde data are shown in Figure 8. [The 300-mb analysis is the same as that shown in Figure 5(c).] A southwesterly diffluent flow pattern generally persisted throughout the troposphere at this time, with wind speeds increasing with altitude and reaching values above 60 ms^{-1} at the 200-mb level. At the 850-mb level, the wind speeds were strongest in the western center of the region. From the 500-mb level and up, the wind speeds were strongest in the southwest of the region. As mentioned previously, this case was associated with severe weather near 99°W and 34°N.

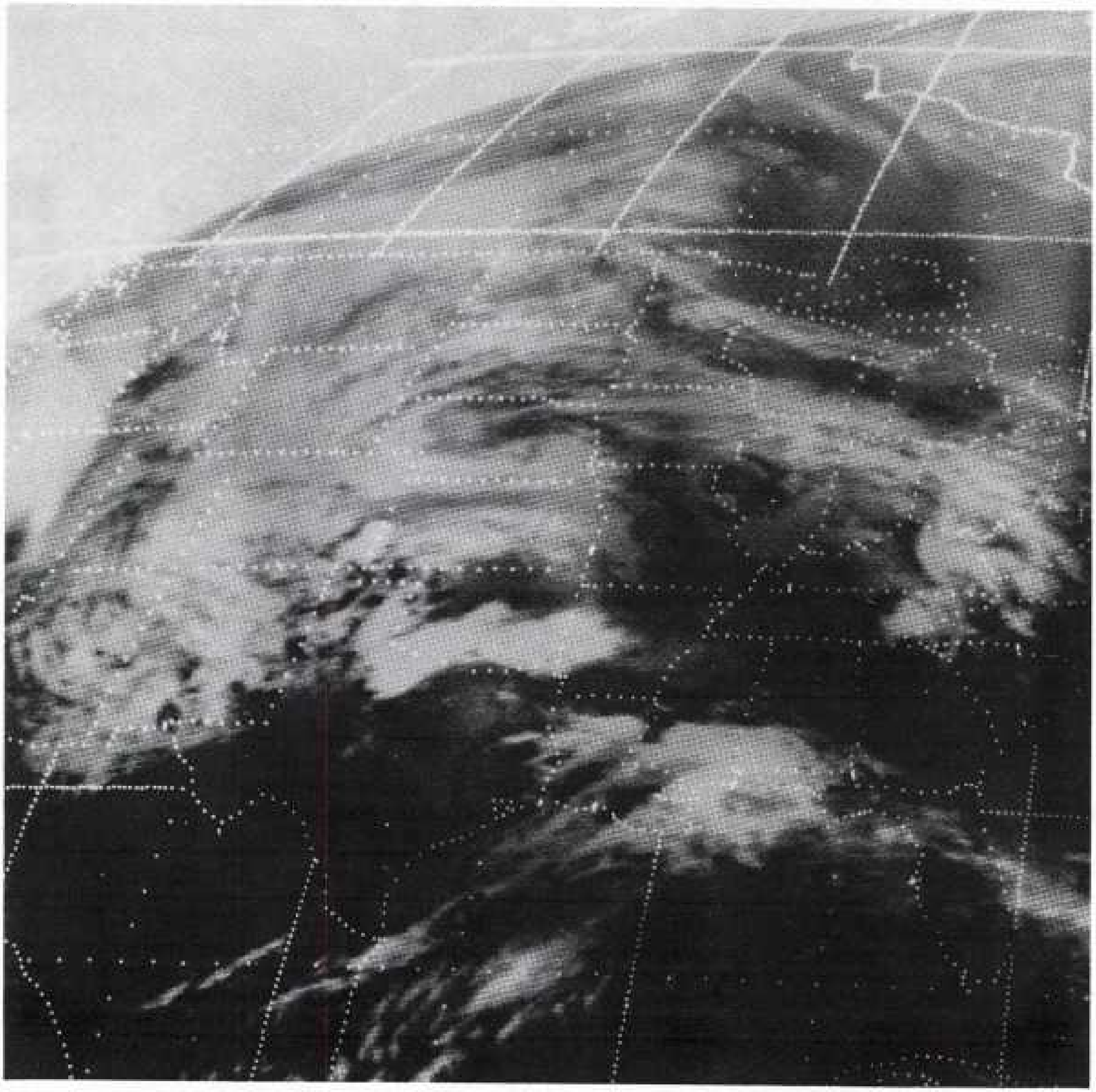


FIGURE 7 GOES-EAST INFRARED IMAGE FOR 2000 GMT 10 APRIL 1979

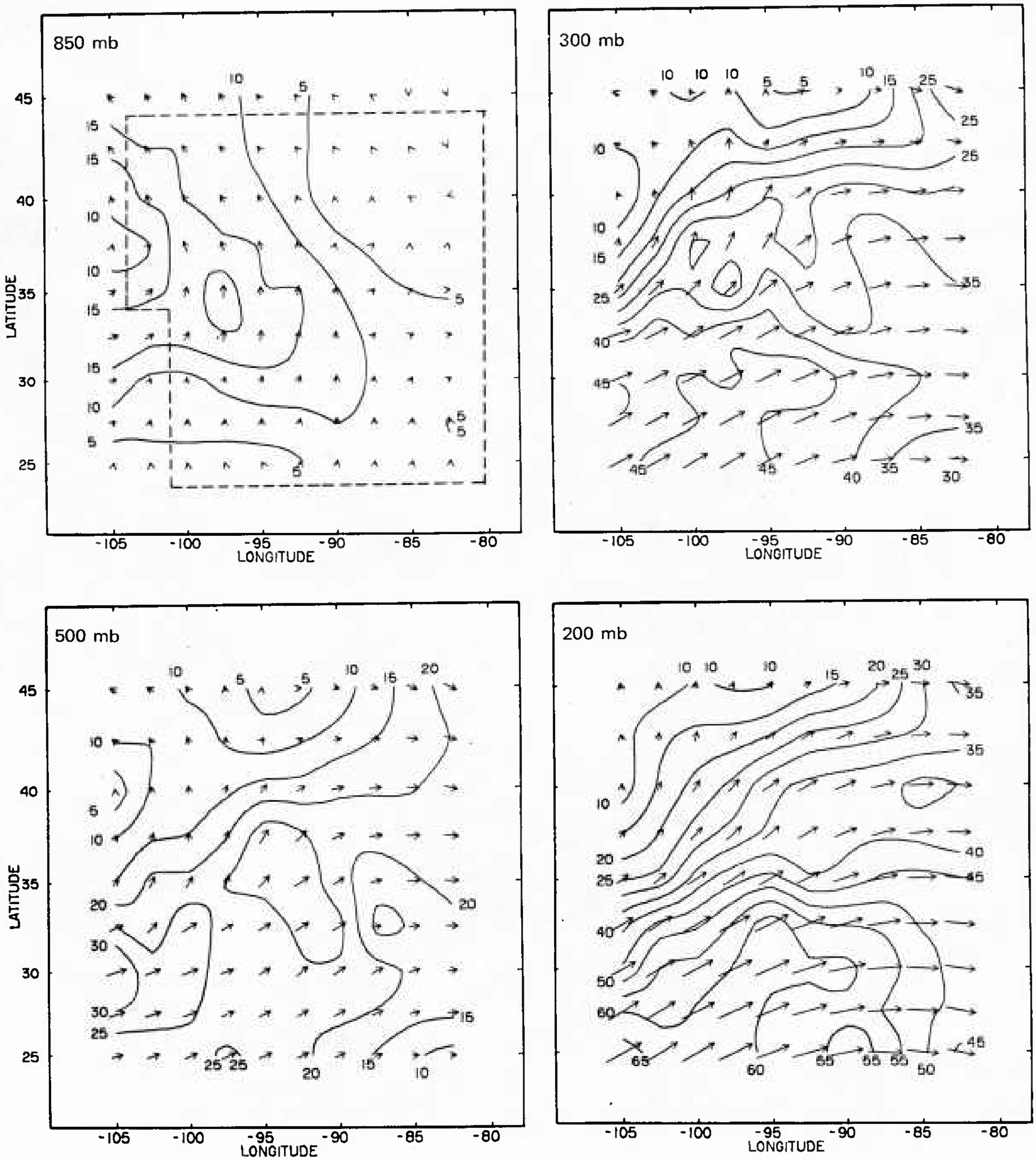


FIGURE 8 WIND FIELDS FOR 2000 GMT 10 APRIL 1979 ANALYZED FROM RADIOSONDE DATA AT 1200 GMT 10 APRIL, 0000 GMT 11 APRIL, AND 1200 GMT 11 APRIL

Isotachs in ms^{-1}.

The graphical results obtained for each of the four techniques are shown in Figures 9-12. The discussion of the results for each of the four techniques is given below.

1. Technique T1 Results

The results for the characteristic profile technique (T1) are shown in Figure 9. In this technique, a downward extrapolation was made from the 300-mb cloud-motion level to 500 mb, giving weaker winds at all points; however, the general pattern at 300 mb was retained. The upward extrapolation to 200 mb was based on knowing the height of the maximum-wind level (MWL), which was determined as described in Section II. The speeds were increased to the MWL and then decreased at higher levels, thereby giving a peaked wind profile. The MWL computed from the thermal-wind reversal varied considerably in height from point to point, between 300 and 200 mb. Thus, the resulting 200-mb wind speeds (Figure 9) also show considerable small-scale variability. Although such variability could be real, it is greater than that analyzed from radiosonde winds (Figure 8) and it therefore appears to be unacceptable.

2. Technique T2 Results

The results for technique T2, which uses the thermal winds to build upward and downward from the cloud-motion level, are shown in Figure 10. The 300-mb cloud-motion field [nondivergent form of Figure 5 (b)] is similar to that shown for the radiosonde analysis in Figure 8, except that the wind speeds are generally lower. The difference appears to be principally attributable to the cloud motions being more representative of a lower level, as will be discussed later. Consistent with this, technique T2 also appears to have made winds at both 500 mb and 200 mb too light in comparison with Figure 8, and to have distorted the winds at the 850-mb level (extrapolated from the 300-mb wind field using the satellite thermal winds).

3. Technique T3 Results

The results for technique T3, which is based on use of the balance equation, are shown in Figure 11. These results are similar to those of technique T2 (Figure 10), except that some of the jet-stream winds are stronger, as would be desired. However, this improvement is noticeable only in the high-speed areas.

4. Technique T4 Results

The results for the eigenvector technique (T4) are shown in Figure 12. [The 300-mb analysis is identical to that of Figure 5(b).] The 500-mb and 200-mb results are fairly similar to those for the radiosonde analyses shown in Figure 8; however, the 850-mb result appears

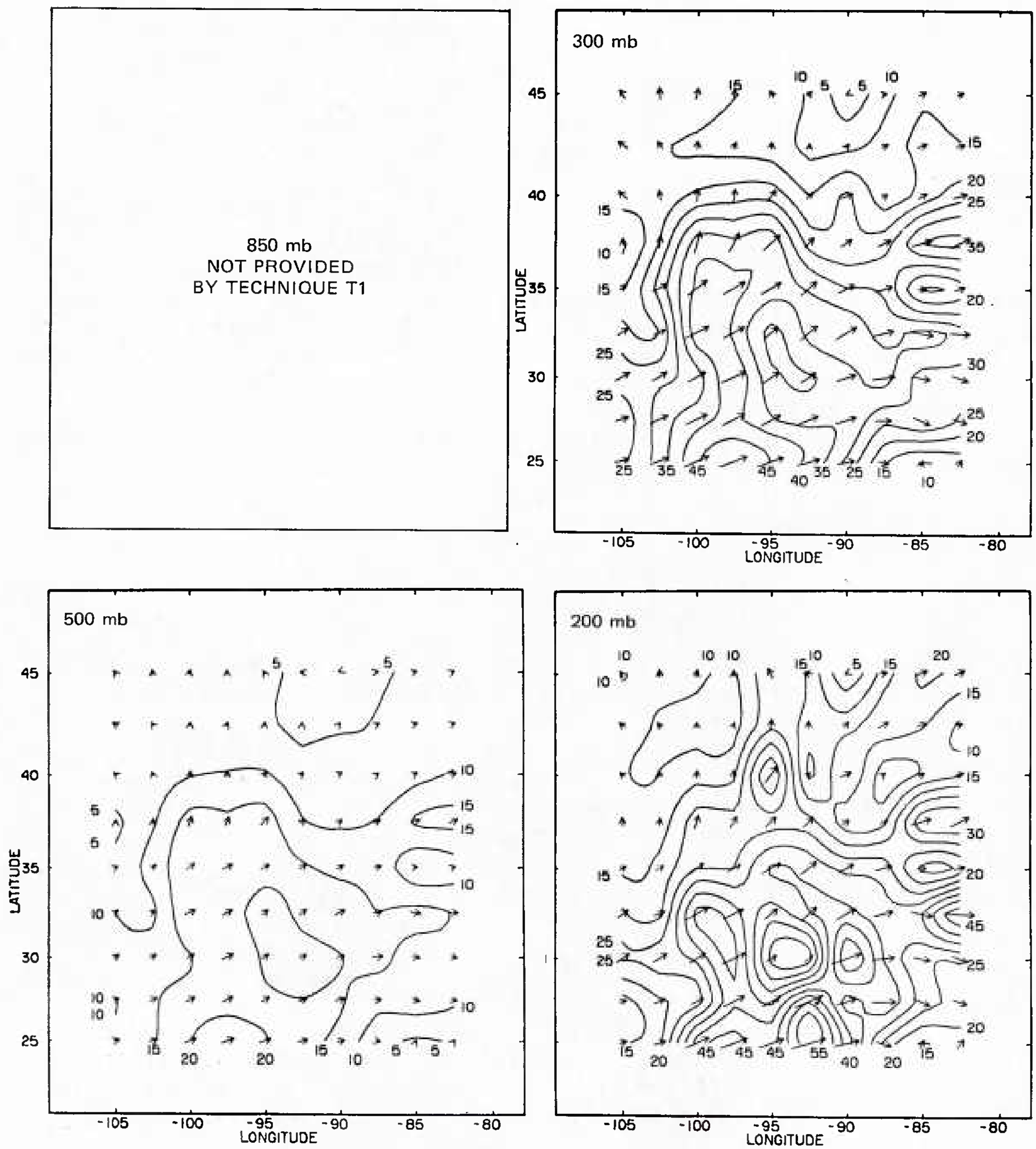


FIGURE 9 WIND FIELDS FOR 2000 GMT 10 APRIL DERIVED USING TECHNIQUE T1
Isotachs in ms^{-1}.

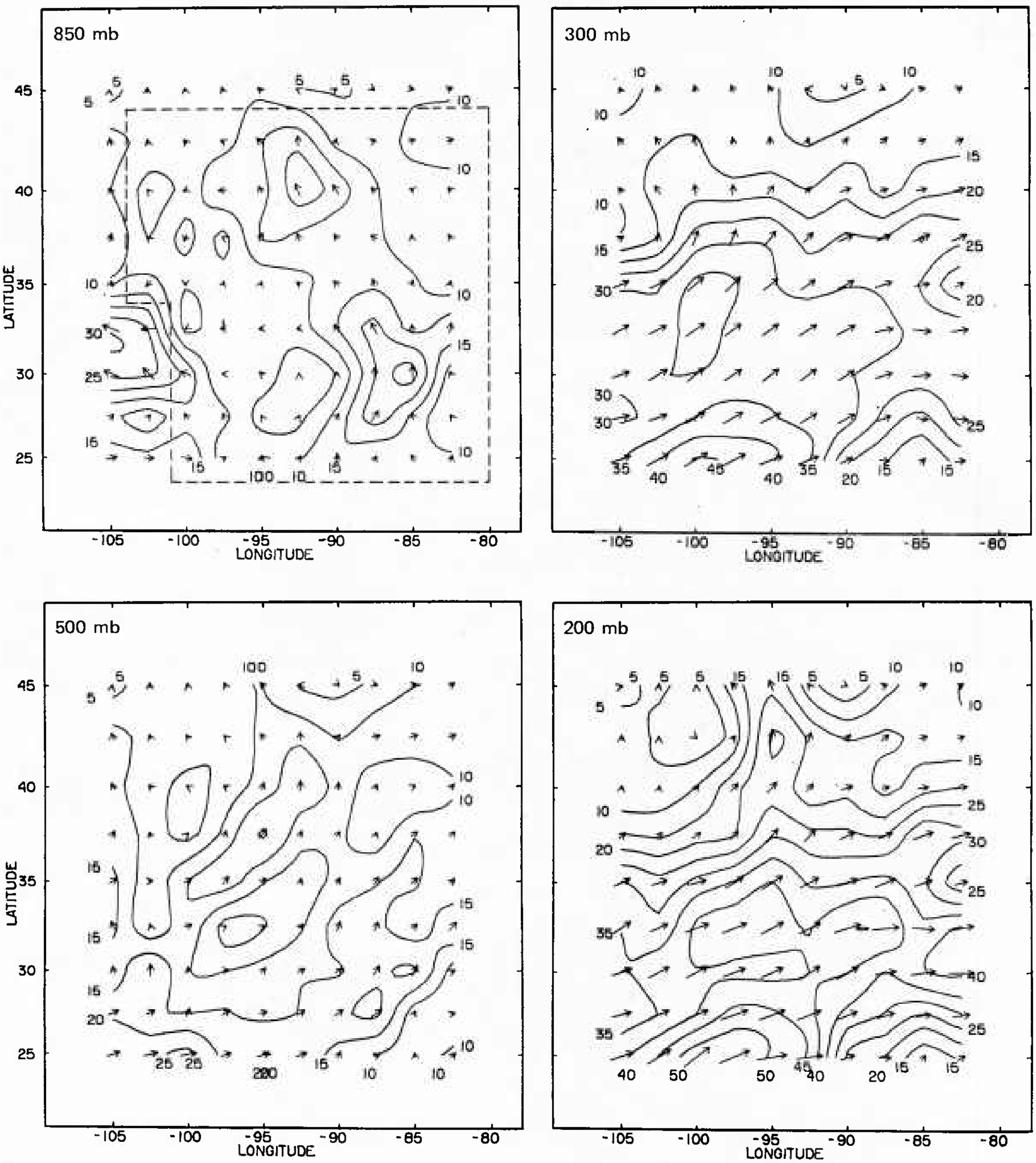


FIGURE 10 WIND FIELDS FOR 2000 GMT 10 APRIL 1979 DERIVED USING TECHNIQUE T2
Isotachs in ms^{-1}.

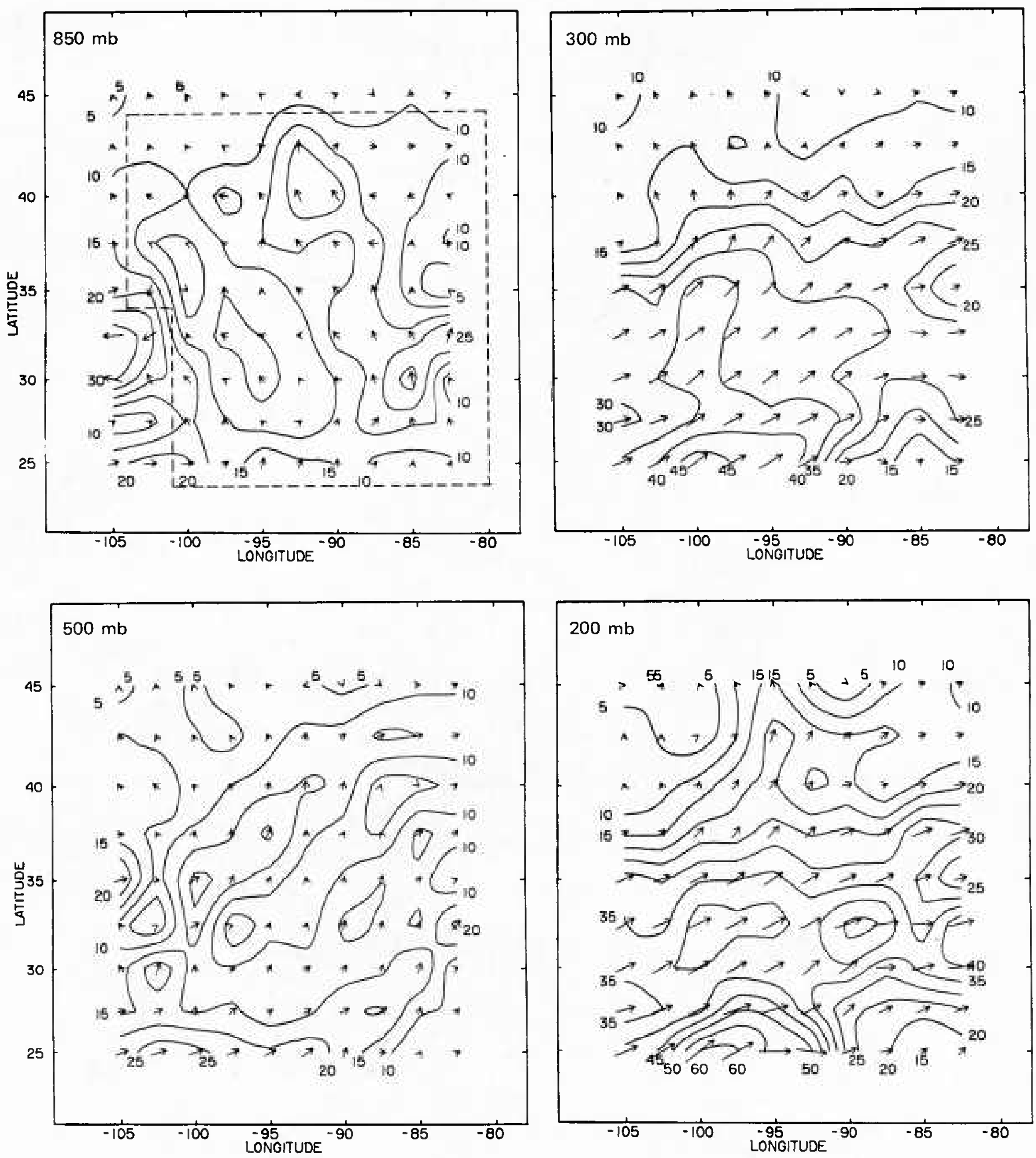


FIGURE 11 WIND FIELDS FOR 2000 GMT 10 APRIL 1979 DERIVED USING TECHNIQUE T3
Isotachs in ms^{-1}.

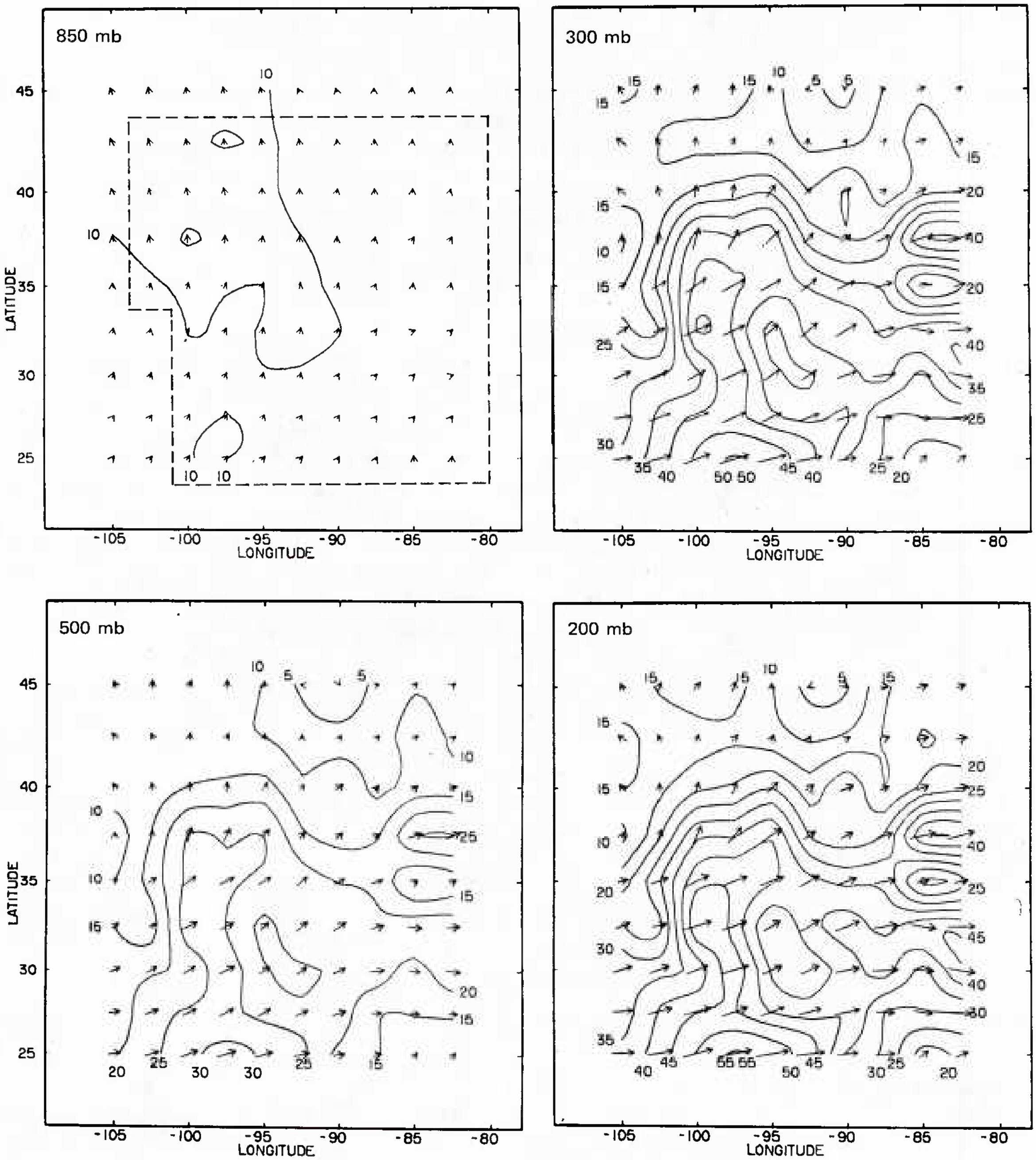


FIGURE 12 WIND FIELDS FOR 2000 GMT 10 APRIL 1979 DERIVED USING TECHNIQUE T4
Isotachs in ms^{-1}.

rather flat. Overall, technique T4 appears to have performed reasonably well, and might be further improved.

5. Summary

In this test case, techniques T2 and T4 performed best, giving a reasonable representation of the winds, although not as good as would be desired. (Technique T2 did not perform very well near the surface.) All of the techniques appear to have been adversely affected by probable errors in the heights of cloud-motion vectors. Also, in this case, there were discrepancies between the temperature fields of the TIROS-N sounding data and radiosonde data that have adversely affected the results.

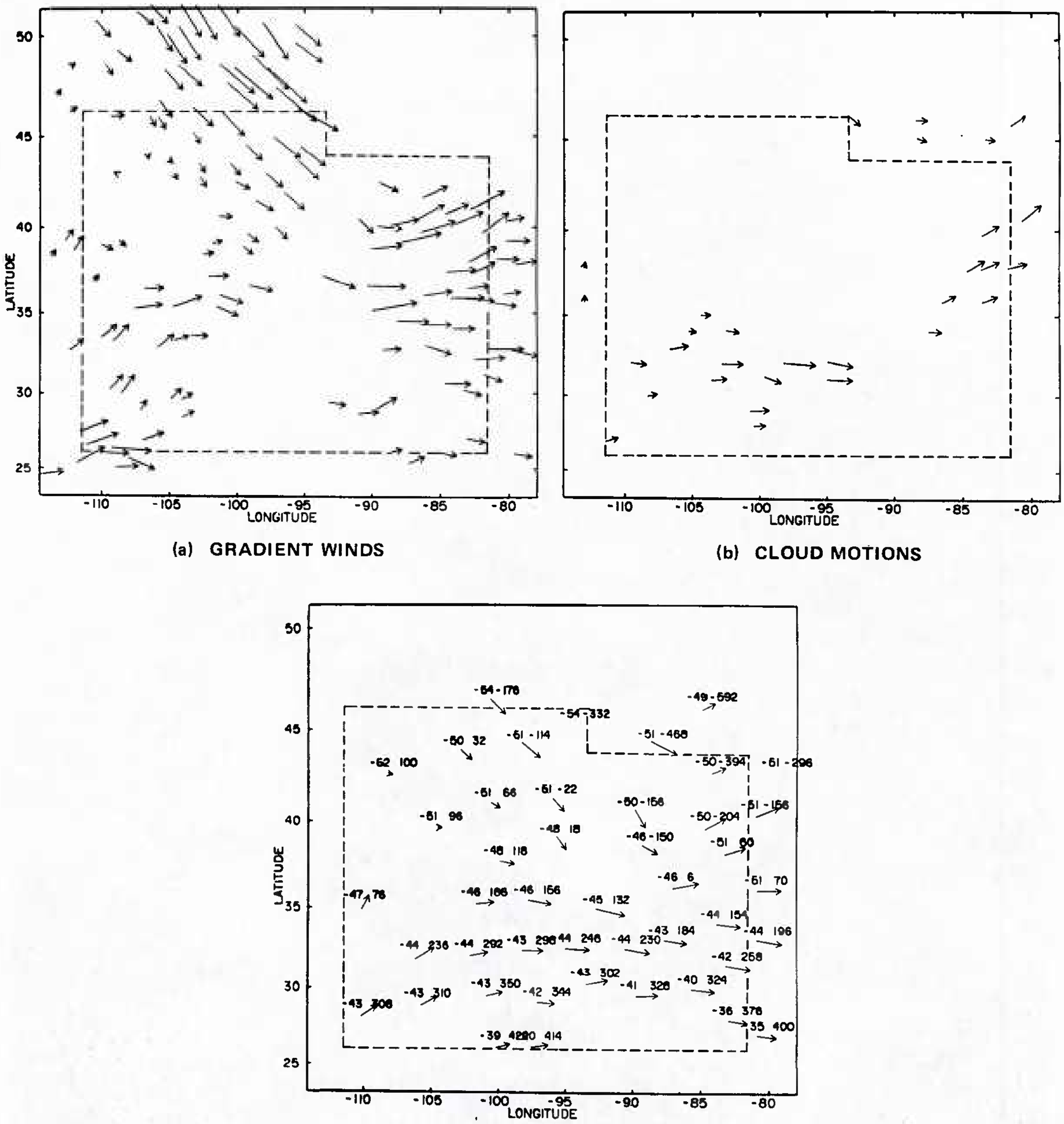
B. Test Case II: 14 March 1979

Figure 13 shows the gradient winds, cloud motions, and radiosonde data at the 300-mb level for the 14 March 1979 case. The satellite gradient-wind data give a good coverage of the region, except in the mid-south and northeast. These satellite gradient winds (and the satellite temperature data) show more internal consistency than did those for Test Case I [Figure 4(a).] The 300-mb cloud motions give only a sparse coverage, but tend to fill-in the data-void areas of the gradient winds. The radiosonde data provide a relatively complete data set covering most of the region. They are for 1200 GMT 14 March 1979 which is only two hours later than the time of the satellite data (1000 GMT). The area enclosed by the dashed line in Figure 13 shows the area used for evaluating the results.

The GOES-EAST satellite infrared image for the Test Case II region for 1000 GMT 14 March 1979 is shown in Figure 14. The 300-mb cloud motions of Figure 13(b) generally lie in areas where Figure 14 depicts high clouds (brightest cloud areas); a large part of the region appears to be clear of high clouds. Although this picture is not of high quality, it reveals the general flow structure (compare with Figure 13) and a frontal system over the eastern U.S.

The 850-, 500-, 300-, and 200-mb wind analyses for the radiosonde data of 1200 GMT 14 March 1979 are shown in Figure 15. At this time, a trough centered over eastern Canada extends south into the eastern United States. At the higher altitudes over the eastern United States, a southern jet merges with a northern jet, with the southern jet appearing to dominate at 200 mb. The wind speeds are generally low over the northeastern and western parts of the region, with high speeds exceeding 55 ms^{-1} at higher altitudes in the north and southeast of the region.

A discussion of the results obtained for each of the four techniques is given below.



(a) GRADIENT WINDS

(b) CLOUD MOTIONS

(c) RADIOSONDE DATA (1200 GMT)

FIGURE 13 AVAILABLE DATA AT THE 300-mb LEVEL OF TEST CASE II, 1000 GMT 14 MARCH 1979

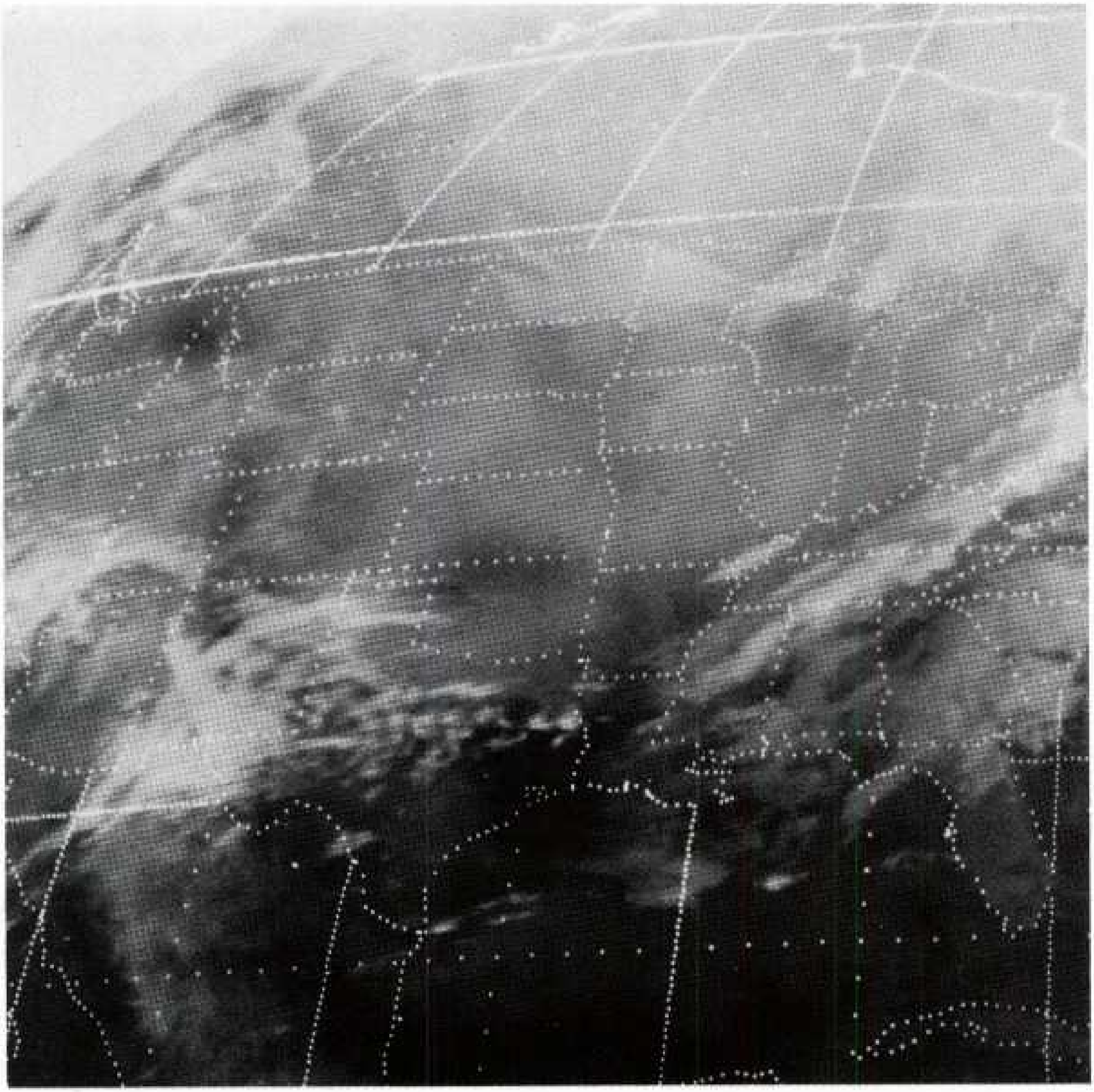


FIGURE 14 GOES-EAST INFRARED IMAGE FOR 1000 GMT 14 MARCH 1979

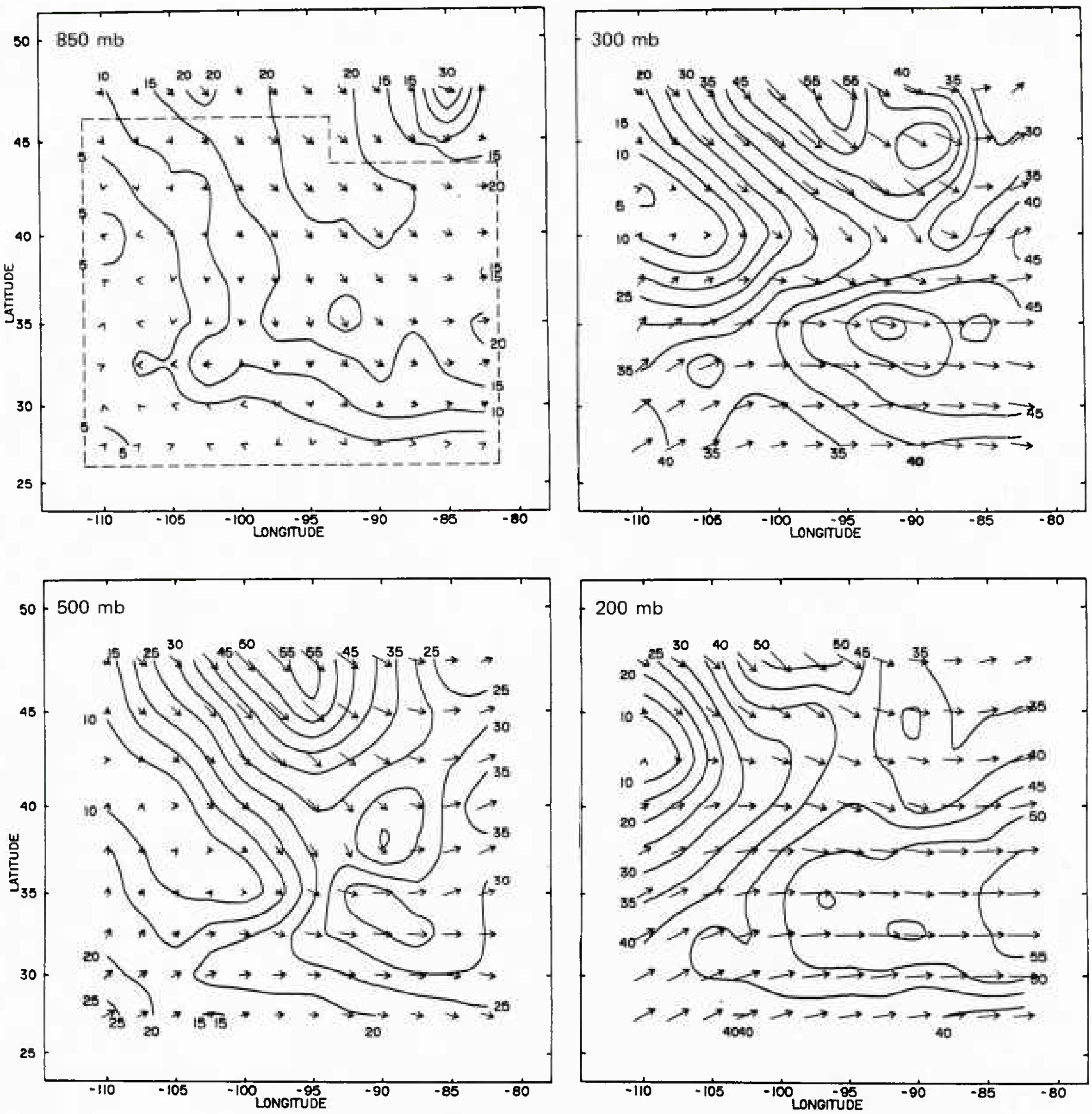


FIGURE 15 WIND FIELDS FOR 1000 GMT 14 MARCH 1979 ANALYZED FROM RADIOSONDE DATA FOR 1200 GMT 14 MARCH 1979

Isotachs in ms^{-1}.

1. Technique T1 Results

As in the 10 April case, technique T1 gave erratic heights for the MWL. Thus, the wind results (not shown) were also very erratic for levels above 300 mb. This method, which is based on an application of characteristic jet-stream profiles, does not appear to be satisfactory in its present form for use in deriving wind profiles from satellite data. Improved results may be possible with this type of approach but would require the development of a family of characteristic wind profiles based on more extensive three-dimensional wind profile information than is currently available.

2. Technique T2 Results

The results for technique T2 are shown in Figure 16. The 300-mb field, which is a nondivergent analysis of the cloud motions of Figure 13(b), is similar to that of the 300-mb radiosonde analysis shown in Figure 15. However, it is even more similar to the 500-mb radiosonde analysis of Figure 15, again suggesting that the cloud motions should have been assigned to a height lower than 300-mb. Consistent with this is the fact that the 500- and 850-mb wind fields for technique T2 in Figure 16 show patterns that appear to be somewhat distorted, and the 200-mb field does not show the broad southern jet of the radiosonde wind field. It appears that the results might have been more satisfactory had the cloud heights been determined more accurately.

3. Technique T3 Results

The results for the balance technique (T3) are not shown. As in Test Case I, they were very similar to the T2 results but with stronger maximum winds, particularly at higher altitudes. Use of the balance relationship appears to give a slight improvement in the high-speed areas, but does not justify the additional computations at this stage of development.

4. Technique T4 Results

The results for the eigenvector technique (T4) are shown in Figure 17. There are no 200-mb results because the gradient-wind data were not available above 250 mb. In this case, technique T4 results appear to be in better agreement with the radiosonde winds at lower levels than are the technique T2 results.

5. Summary

The March test case had few cloud-motion measurements. However, the results were similar to those for the 10 April case. Techniques T2

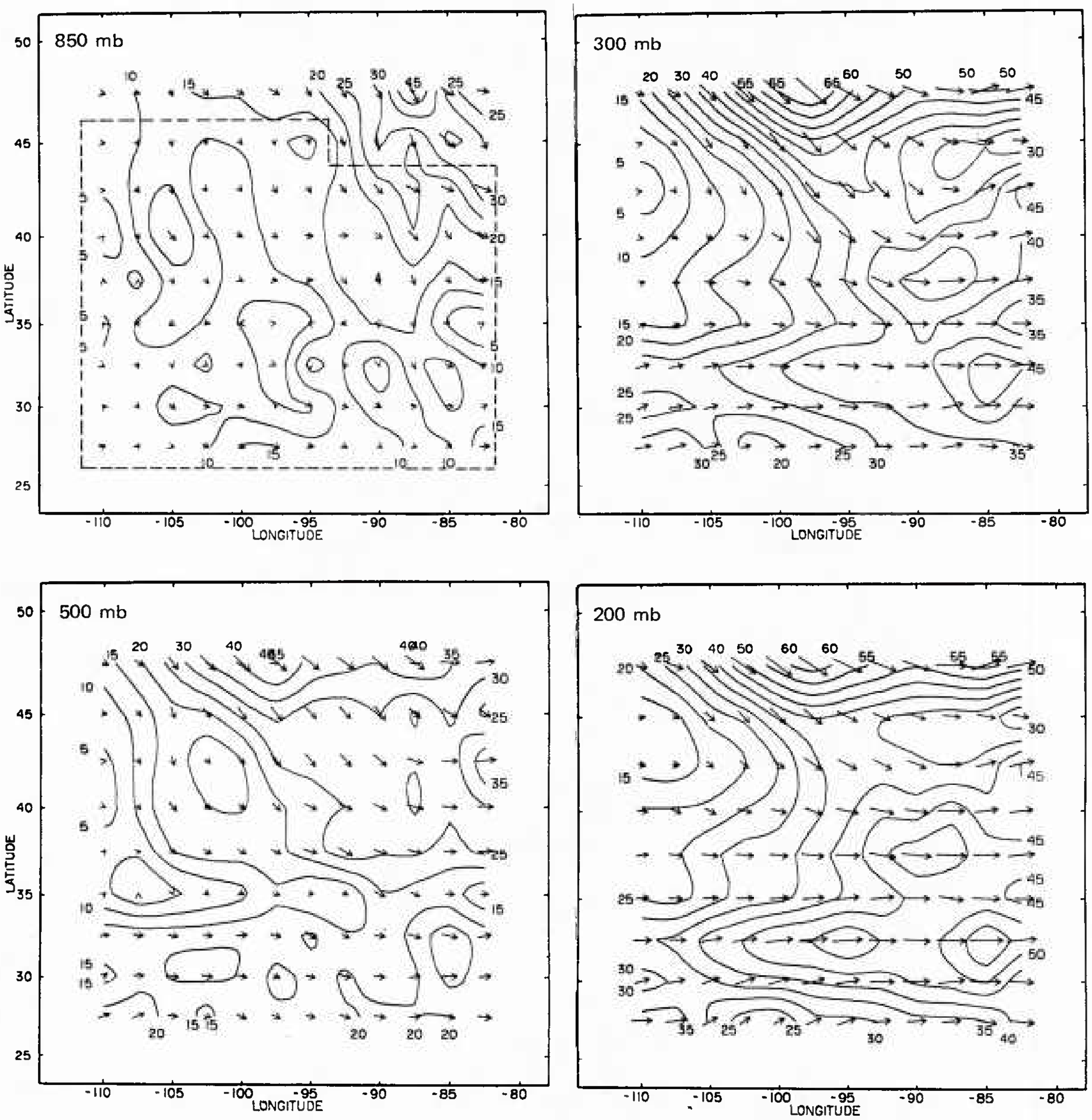


FIGURE 16 WIND FIELDS FOR 1000 GMT 14 MARCH 1979 DERIVED USING TECHNIQUE T2
Isotachs in ms^{-1}.

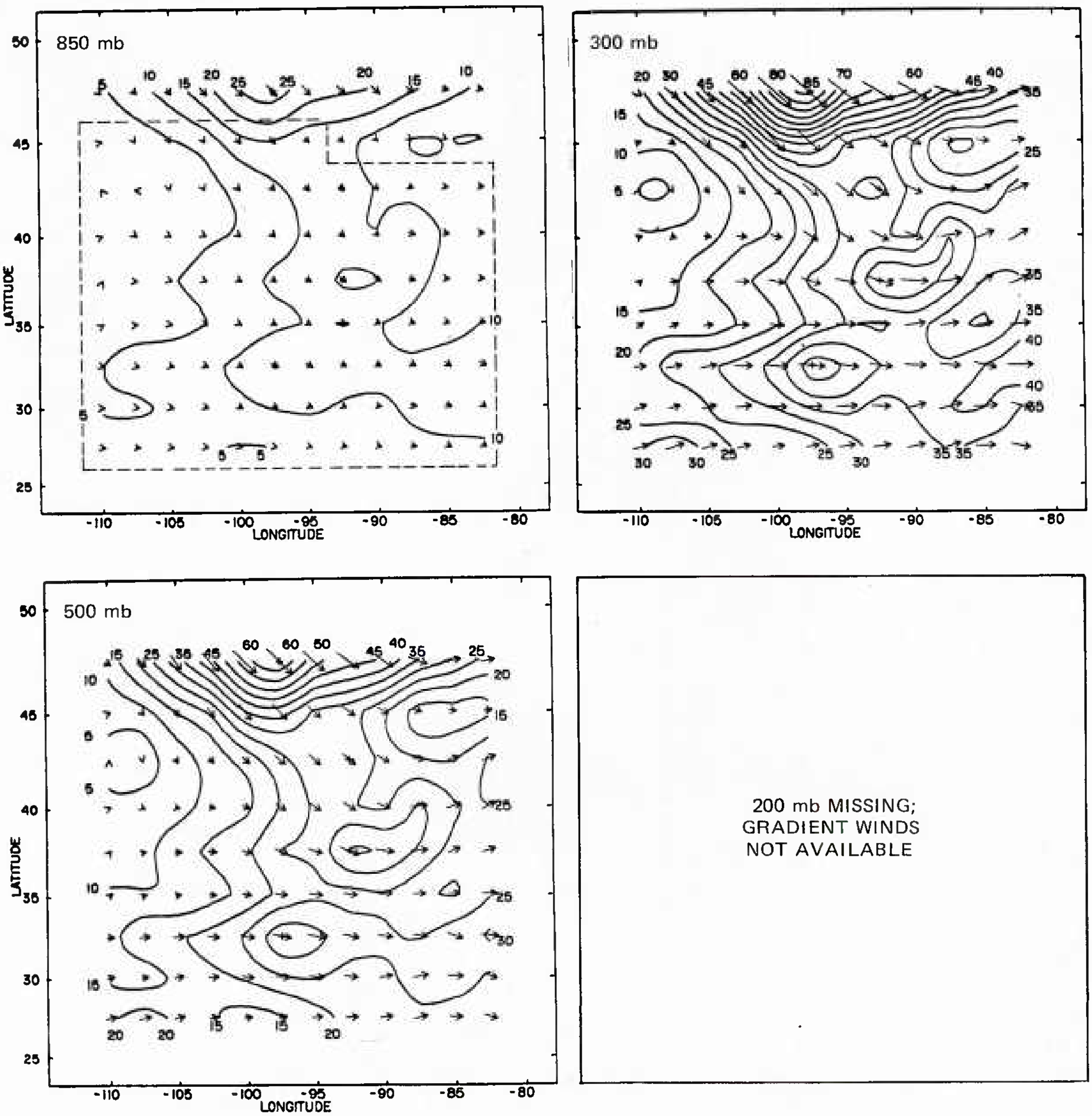


FIGURE 17 WIND FIELDS FOR 1000 GMT 14 MARCH 1979 DERIVED USING TECHNIQUE T4
Isotachs in ms^{-1}.

and T4 performed the best and gave fair agreement with the radiosonde-wind profiles. The analyses again appeared to be adversely affected by the assigned cloud-motion heights.

C. Test Case III: 2 May 1979

Figure 18 shows the gradient winds, cloud motions and radiosonde data at the 300-mb level for the 2 May 1979 test case. In this test case, both the gradient winds and cloud motions give reasonably good coverage of the region. There are no gradient winds in the south and the southeast of the region, and no cloud motions in the north and west of the region (except for a cluster in the northwest corner). However, the cloud motions and gradient winds tend to complement each other at the 300-mb level. The radiosonde data are for 1200 GMT 2 May 1979, which is only two hours later than satellite data (1000 GMT). The area enclosed within the dashed line was used for evaluating the results.

The GOES-WEST satellite infrared image for the Test Case III region and for 1015 GMT 2 May 1979 is shown in Figure 19. The cloud features reveal a southwesterly flow of high-level air from the Pacific into northwestern Mexico, and a strong development within the center of the trough over Arizona and Colorado. The high-cloud areas are consistent with the 300-mb cloud motions of Figure 18.

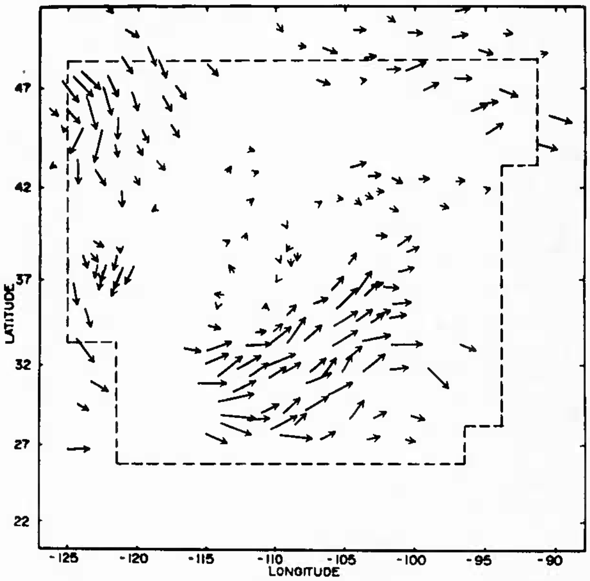
The 700-,* 500-, 300-, and 200-mb wind analyses of the radiosonde data for 1200 GMT 2 May 1979 are shown in Figure 20. A fairly deep trough was situated over the westernmost U.S. with very light winds extending up through the atmosphere at the center of the trough over northern Colorado. Strong northerly winds existed just off the west coast and strong westerly winds across the southern border of the country, with speeds reaching up to 45 ms^{-1} at higher altitudes. The wind field is fairly uniform throughout the upper troposphere (above 500 mb). The analyses in the southwest corner of the analysis region are extrapolated values and are not very meaningful [see Figure 18(a)].

Only techniques T2 and T4 were tested with this Test Case III; a discussion is given below.

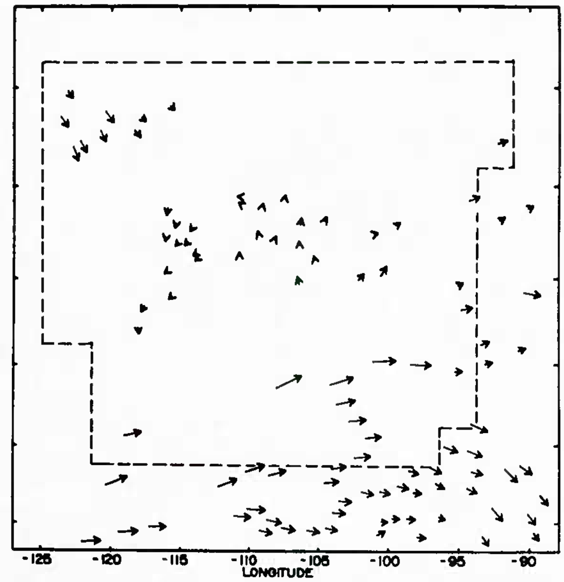
1. Technique T2 Results

The results for technique T2, which are shown in Figure 21, are reasonably good--particularly for the upper two levels (300 and 200 mb). The technique has produced unrealistically strong winds in the southwest of the region at the lower two levels (700 and 500 mb); this area is at the boundary of the thermal-wind data. The high winds (>45 ms^{-1}) in the south of the region of the 300-mb radiosonde field (Figure 20) are stronger

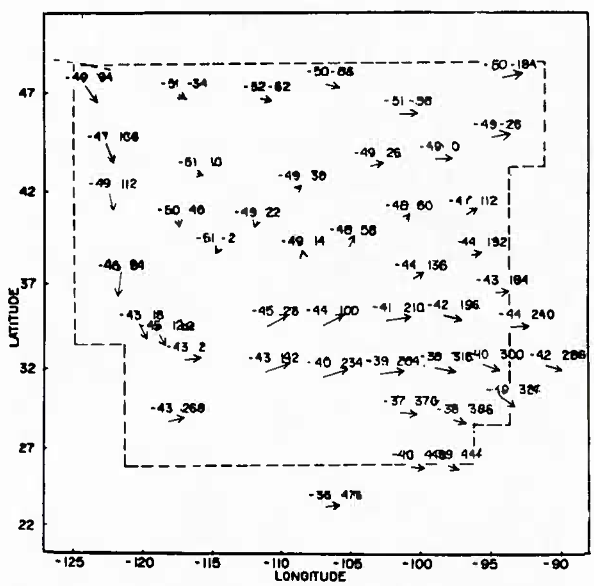
*The 700-mb level is shown in this test case in place of the 850-mb because the 850-mb level was frequently below the level of the terrain.



(a) GRADIENT WINDS



(b) CLOUD MOTIONS



(c) RADIOSONDE DATA (1200 GMT)

FIGURE 18 AVAILABLE DATA AT THE 300-mb LEVEL, TEST CASE III, 1000 GMT 2 MAY 1979

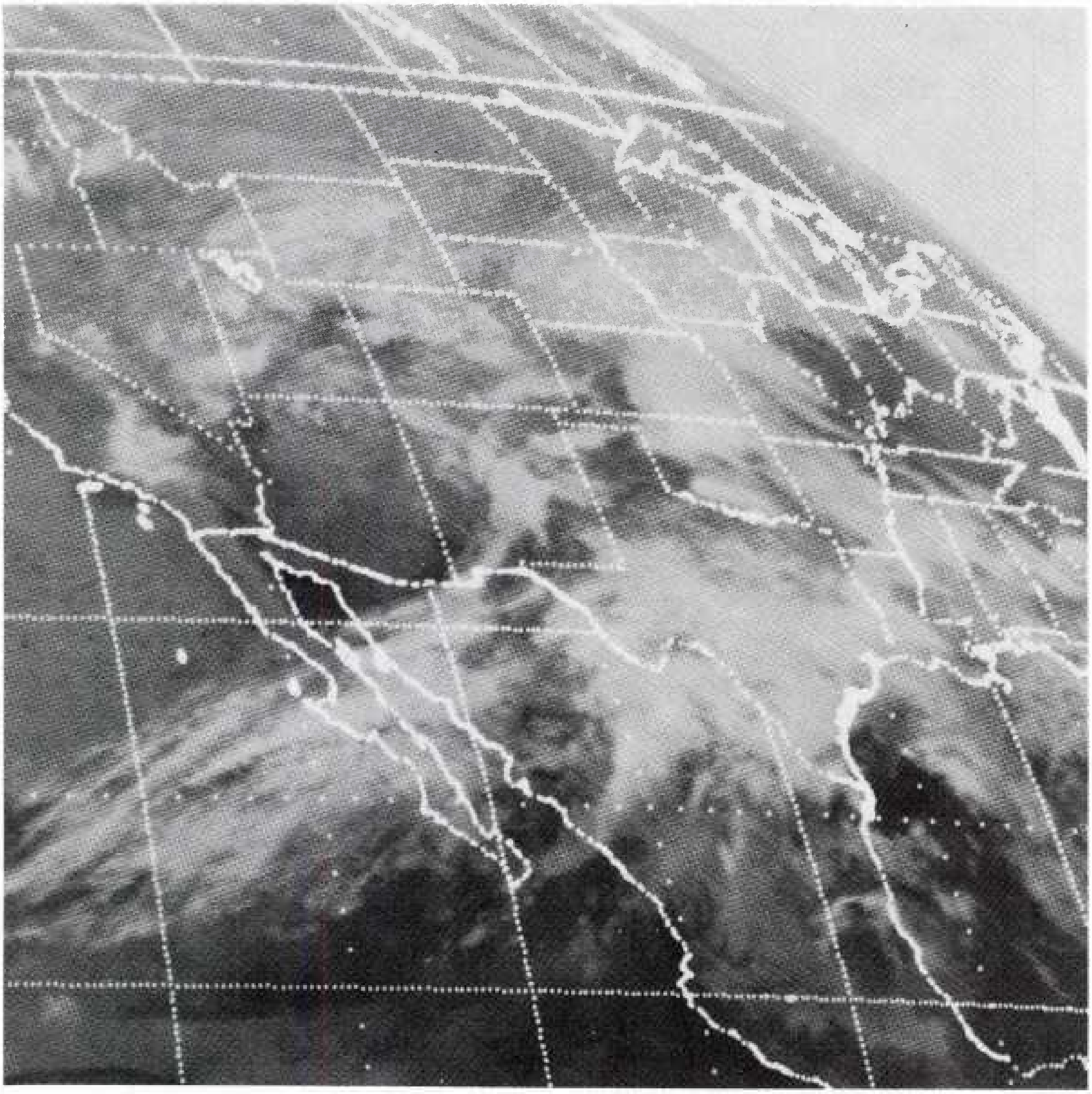


FIGURE 19 GOES-WEST INFRARED IMAGE FOR 1015 GMT 2 MAY 1979

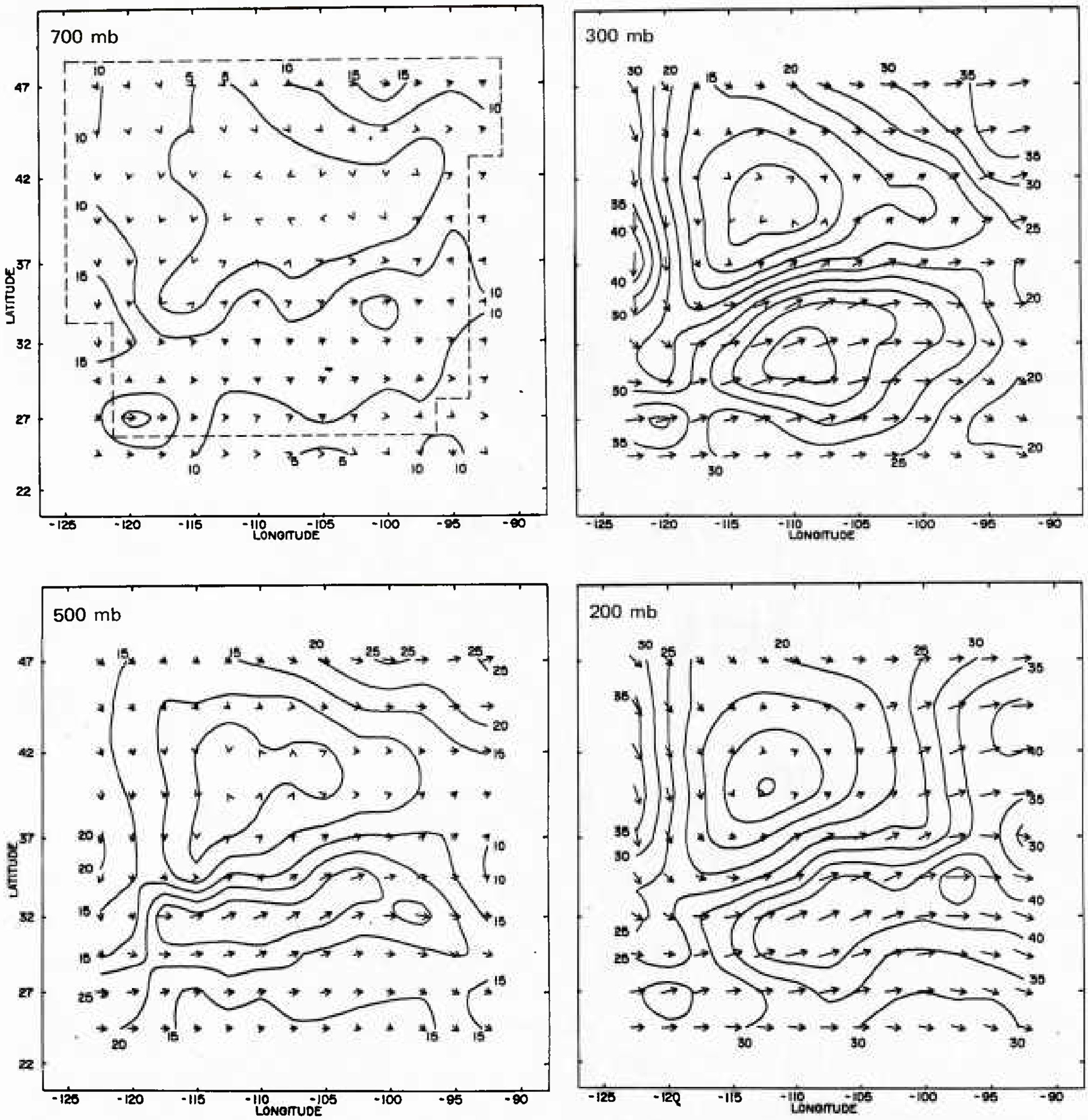


FIGURE 20 WIND FIELDS FOR 1000 GMT 2 MAY 1979 ANALYZED FROM RADIOSONDE DATA FOR 1200 GMT 2 MAY 1979

Isotachs in ms^{-1}.

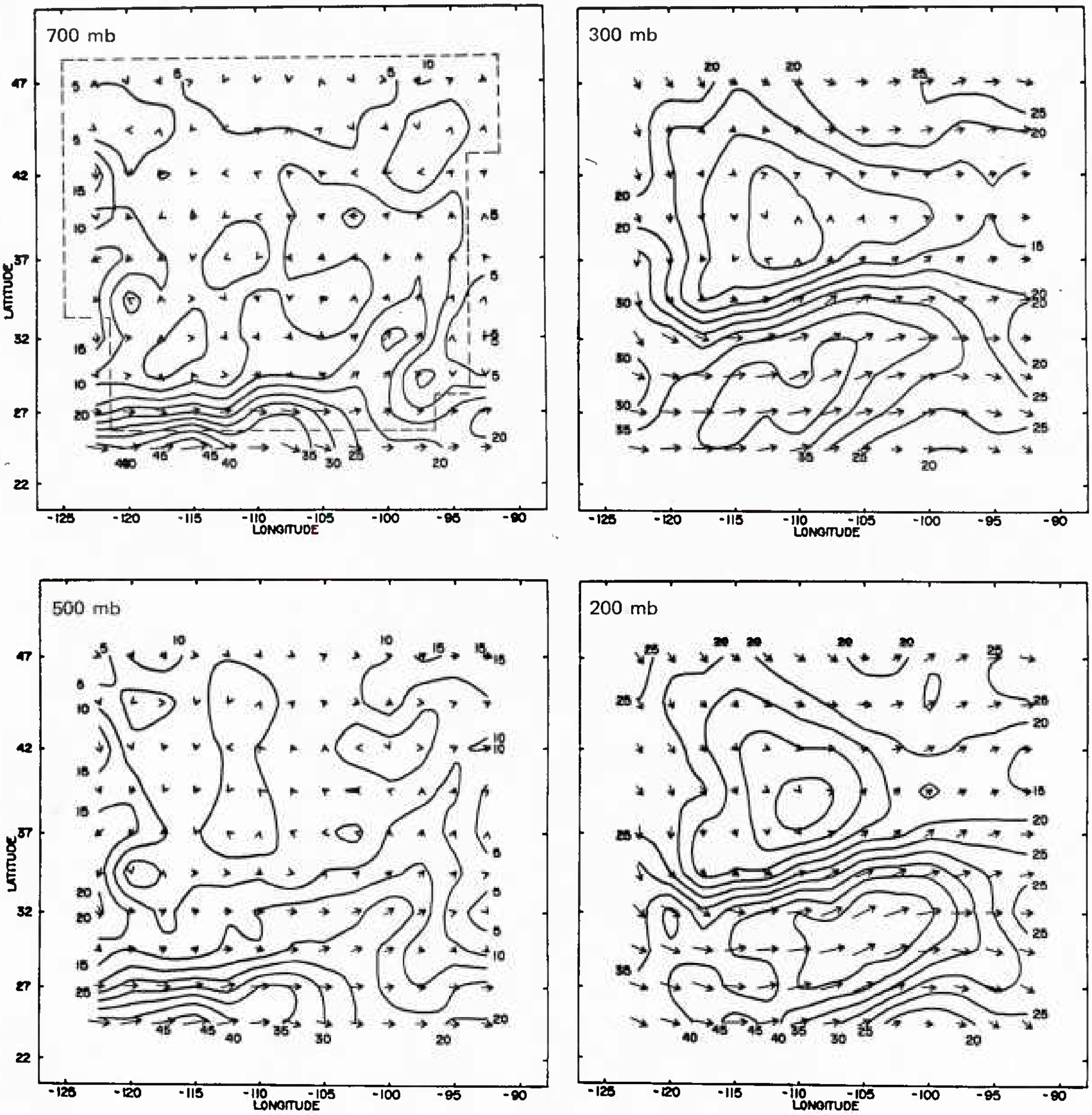


FIGURE 21 WIND FIELDS FOR 1000 GMT 2 MAY 1979 DERIVED USING TECHNIQUE T2
Isotachs in ms^{-1}.

than those (>40 ms^{-1}) for technique T2 (Figure 21); this could possibly be caused by a bias toward mid-range speeds associated with manual tracking of cloud motions (Leese et al., 1971).

2. Technique T4 Results

The results for technique T4, which are shown in Figure 22, are also relatively good. The results for the two higher levels (300 and 200 mb) are similar to those of technique T2; but the T4 results for the lower two levels are definitely superior, and are quite close to those of the radiosonde wind analyses.

3. Summary

In this case, only techniques T2 and T4 were tested. Good results were obtained, probably because of better satellite data than in the other cases and a closer agreement between the thermal winds and actual wind shear.

D. Root-Mean-Square Errors (rmse) and Scatter Diagrams

A summary of the results of the testing are shown in Table 1. This table lists the rmse values for each technique and for the gradient wind, and the values for the mean wind in each layer. The vector rmse values were calculated at each level using the formula:

$$\text{rmse} = \left(\sum_{n=1}^{N} \left| \mathbb{M} - \mathbb{V} \right|^2 / N \right)^{1/2} \tag{6}$$

where $\mathbb{M}$ and $\mathbb{V}$ are the technique estimated wind vector and the radiosonde wind vector at some grid point, and the summation is made over N grid points. The grid points used in the rmse calculations were those that fell within the areas that contained both satellite temperature profile data and radiosonde data (areas enclosed within dashed lines shown in preceding figures). As shown by this table, technique T1 did not perform well, particularly at 200 mb in the 10 April and 14 March cases, and its testing was discontinued. It apparently could not adequately delineate the radiosonde MWL, resulting in poor results above the cloud-motion level.

The rmse values for technique T3 are only slightly different from those for technique T2 and are actually slightly higher. Since the computations using the balance equation are extensive, use of technique T3 does not appear to be warranted at this time. Technique T3 was also not tested with the 2 May case.

The two remaining techniques, T2 and T4, appear to give reasonable rmse values. The eigenvector technique (T4) gives lower rmse values

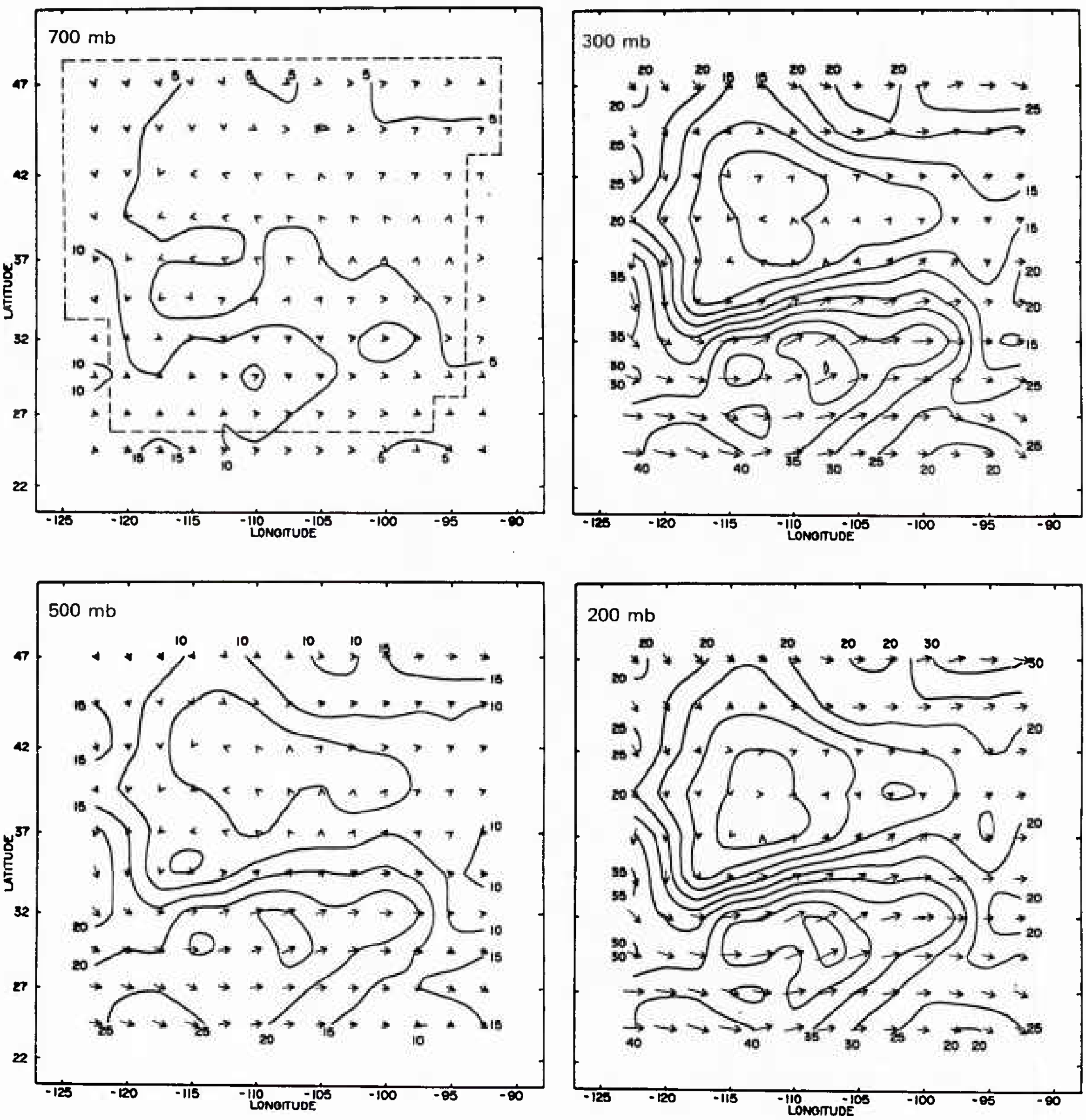


FIGURE 22 WIND FIELDS FOR 1000 GMT 2 MAY 1979 DERIVED USING TECHNIQUE T4
Isotachs in ms^{-1}.

Table 1

VECTOR RMSE OF WINDS DERIVED BY TECHNIQUES T1, T2, T3, T4 COMPARED TO RADIOSONDE WINDS*
(All values in ms^{-1})

Case/Pressure	Mean Wind Speed	Vector Rmse				
		Gradient Wind	T1	T2	T3	T4
10 April 1979						
850 mb	10.7	5.9	--	12.4	12.9	6.0
500	19.2	10.0	9.0	12.4	13.1	7.9
300	33.4	17.3	11.4	11.4	11.6	11.8
200	43.4	22.5	22.7	17.4	13.0	18.0
14 March 1979						
850 mb	13.1	7.7	--	10.8	--	9.2
500	25.0	10.3	13.4	11.7	12.5	9.6
300	38.2	12.3	11.9	11.3	11.6	11.8
200	43.4	--	19.8	10.9	11.8	--
2 May 1979						
700 mb	9.8	6.5	+	10.9	+	5.3
500	17.0	8.6		11.2		7.2
300	28.1	13.0		9.4		10.2
200	29.6	13.2		10.9		11.1

*The radiosonde wind errors associated with high-wind conditions (or low elevation angles) are 3 ms^{-1} at 700 mb, 6 ms^{-1} at 500 mb, 8 ms^{-1} at 300 mb, and 11 ms^{-1} at 200 mb (NWS, 1967/1977).

+Testing discontinued: See text.

below the cloud-motion level (300 mb). This is reasonable, since these values are based not only on satellite cloud-motion and thermal-wind data, but also on known surface geostrophic-wind values. If technique T2 were modified to use the satellite thermal winds to interpolate wind values between the cloud motions and surface geostrophic winds, the results for T2 would probably be very similar to those for T4. Above the cloud-motion level, both techniques T2 and T4 give similar rmse values.

The calculated rmse values for the satellite gradient winds are also shown in Table 1. The values listed for the 500-mb level (10.0, 10.3 and 8.6 ms^{-1}) are very close to the rmse value (9.9 ms^{-1}) given by Thomasell and Shen (1980) for gradient winds derived from NIMBUS 6 microwave data. However, as shown for the 10 April case, the gradient wind errors can increase dramatically with height, indicating the importance of introducing the cloud-motion values at some high level, such as the 300-mb level.

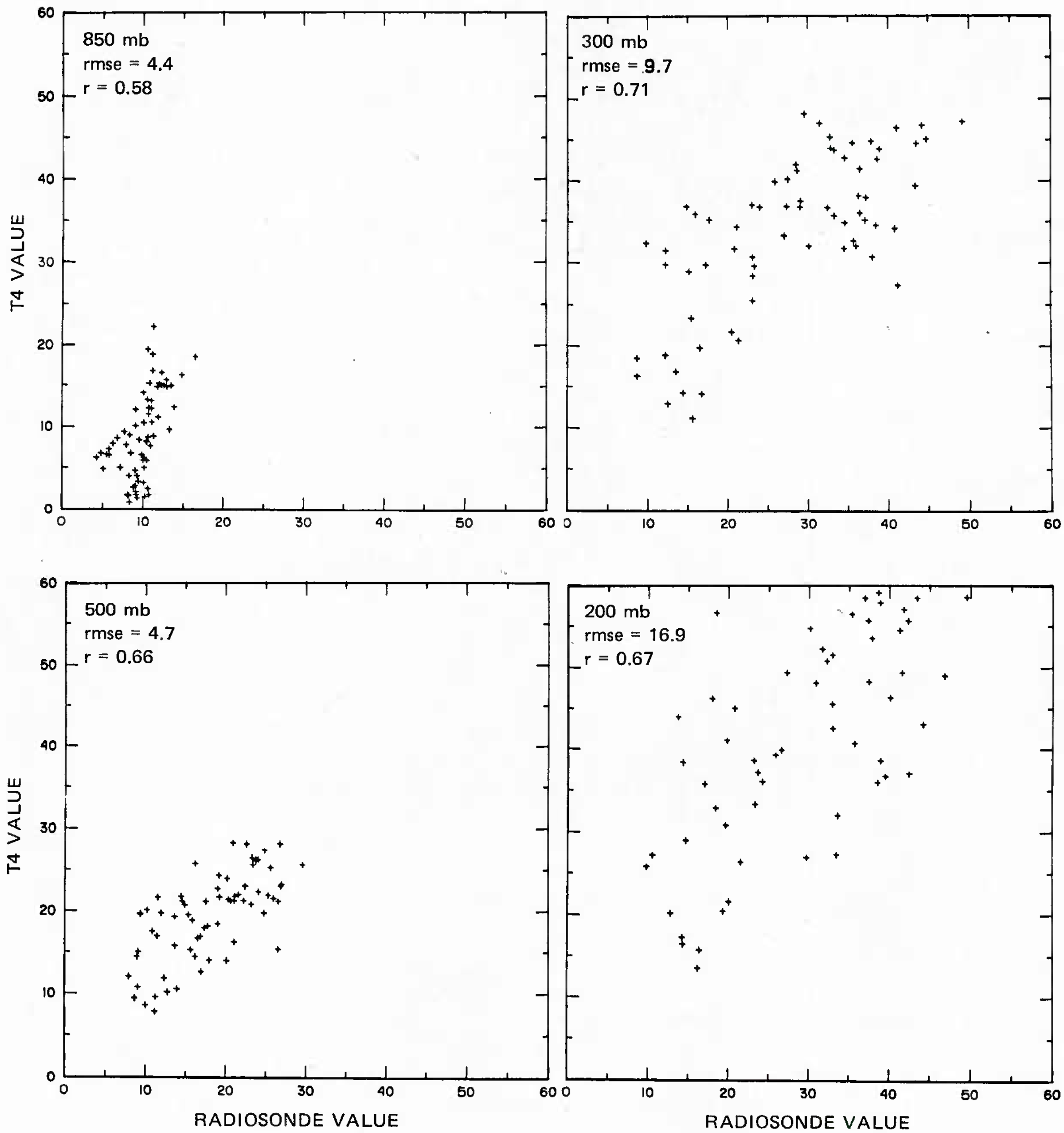
The rmse values for the most promising techniques (T2 and T4) were based on comparisons with radiosonde measurements which can also contain large errors (listed in footnote of Table 1). The T2 and T4 results are superior to the use of purely gradient winds and their rmse values could probably be significantly reduced by the use of more accurately processed cloud-motion heights and thermal winds from satellite data.

Scatter diagrams for the most successful technique (T4) in its application to Test Cases I, II, and III are shown in Figures 23, 24, and 25. These figures compare both the wind speeds [part (a)] and directions [part (b)] computed by T4 with the corresponding radiosonde values. In the wind direction scatter diagrams, all points shown within the 0 to 360° range are duplicated at points outside this range for continuity purposes. The calculated rmse for the wind speeds and directions are also given in the figures, which are, of course, different from the vector rmse given in Table 1. Correlation coefficients (r) are also given for the wind speeds.

E. Cloud-Motion Height Errors

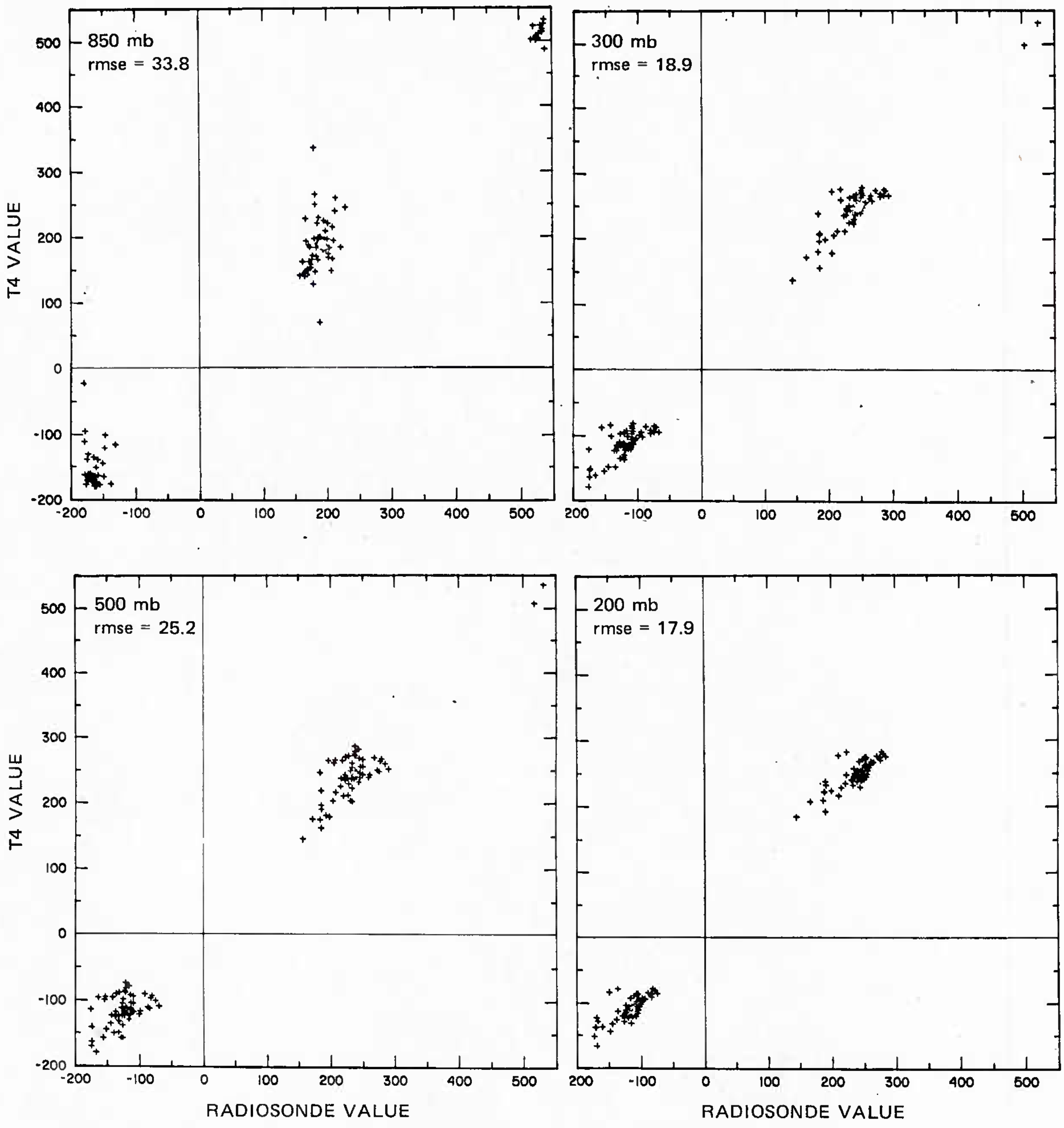
In this study all cloud motions used were those assigned a cloud height of 300 mb. However, the cloud-motion measurements in these test cases had been simply set at a mandatory level that was nearest to the height estimated from the infrared radiance value.

The graphical displays of the results generated for all of the test cases (Section IV-A to IV-C) indicated that the cloud motions had generally been assigned to a level too high in the atmosphere. To assess this more objectively, calculations were made to determine the level of best fit; that is, the level at which the cloud motions are in best agreement with the radiosonde wind field. Figure 26 shows the rmse that were obtained when the 300-mb cloud motions were compared to the radiosonde winds at different



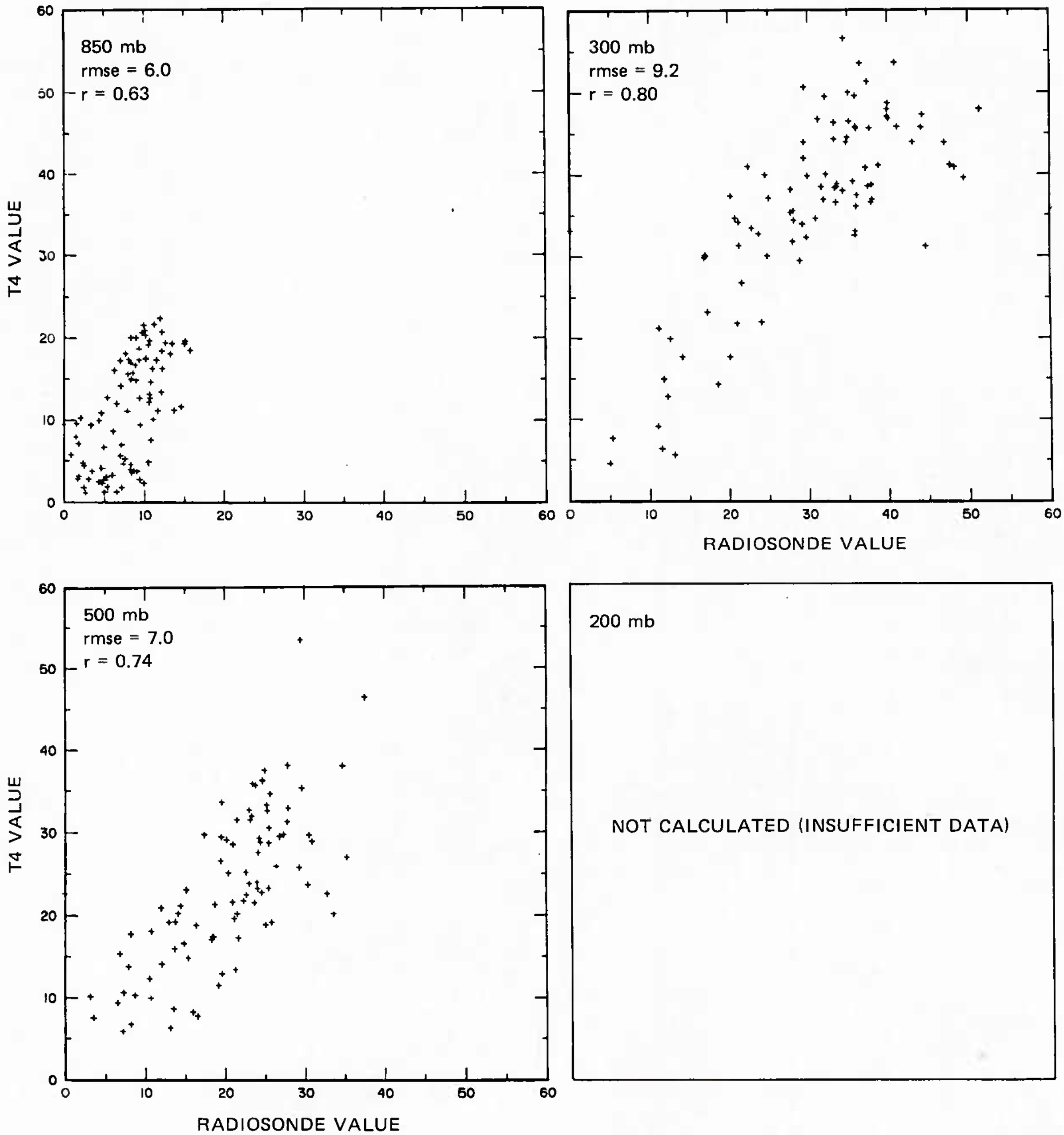
(a) WIND SPEEDS — ms^{-1}

FIGURE 23 SCATTERGRAM SHOWING T4 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE I, 10 APRIL 1979



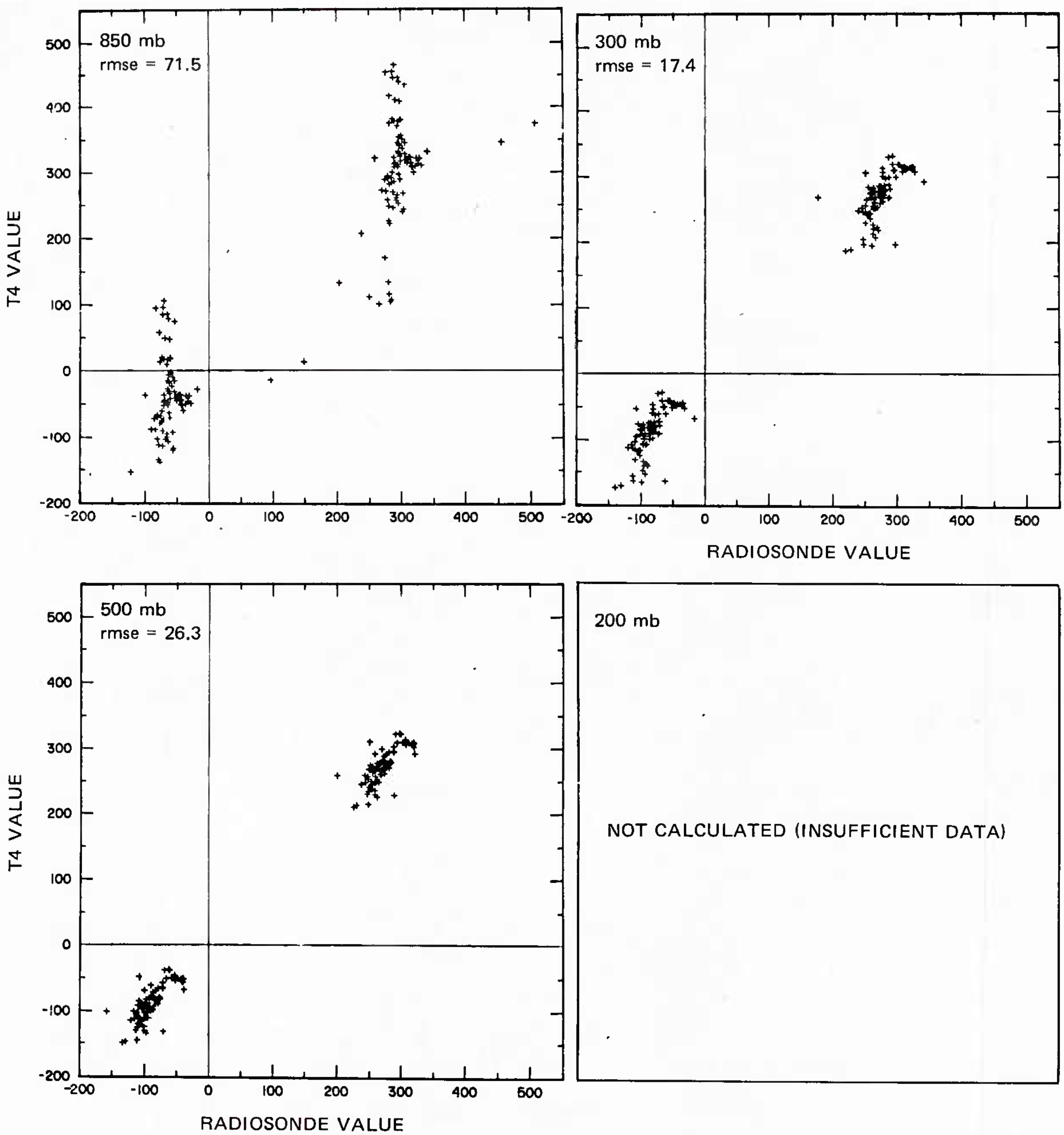
(b) WIND DIRECTION — degrees

FIGURE 23 SCATTERGRAM SHOWING T4 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE I, 10 APRIL 1979 (Concluded)



(a) **WIND SPEEDS — ms^{-1}**

FIGURE 24 SCATTERGRAM SHOWING T4 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE II, 14 MARCH 1979



(b) WIND DIRECTIONS — degrees

FIGURE 24 SCATTERGRAM SHOWING T4 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE II, 14 MARCH 1979 (Concluded)

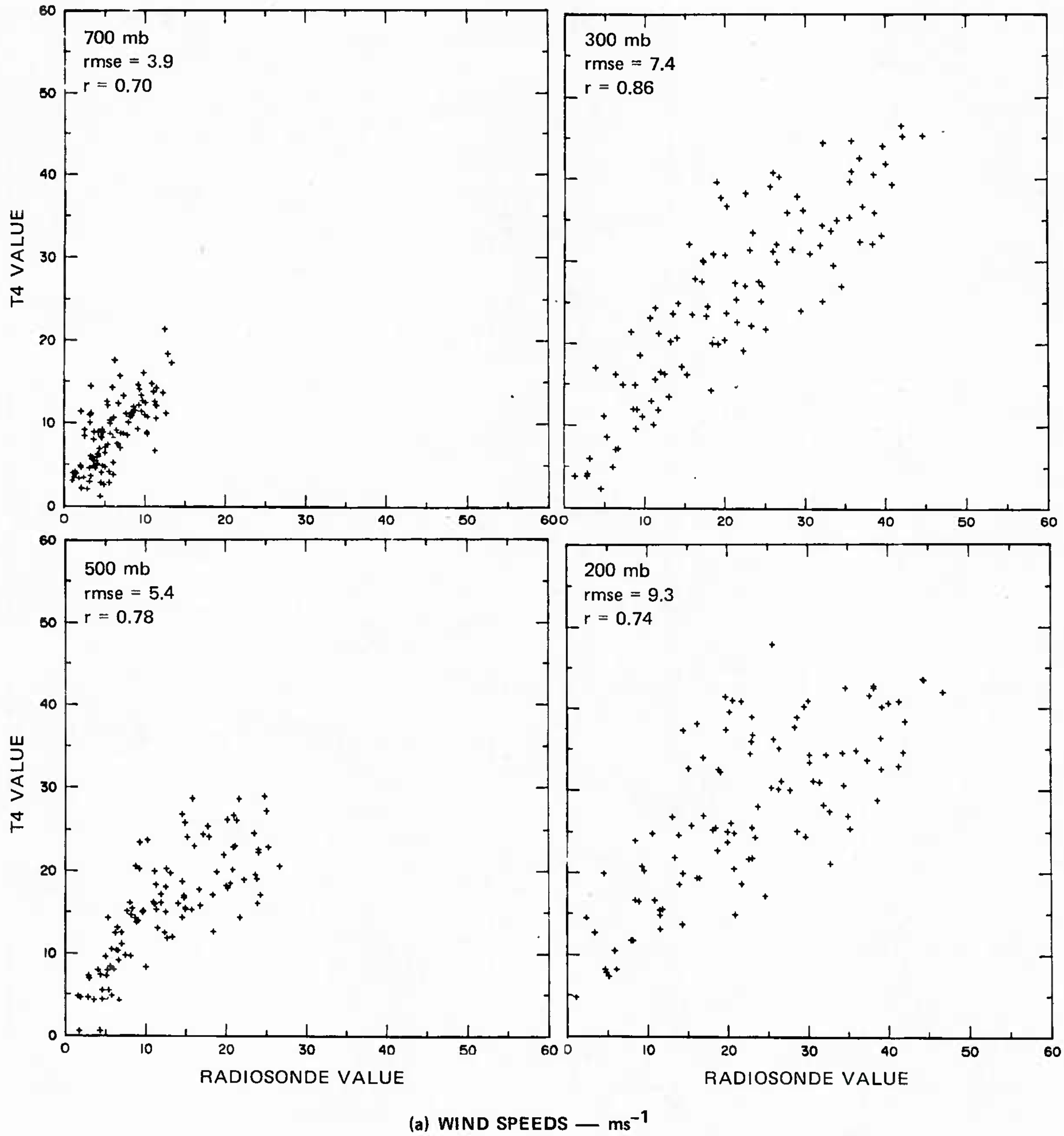
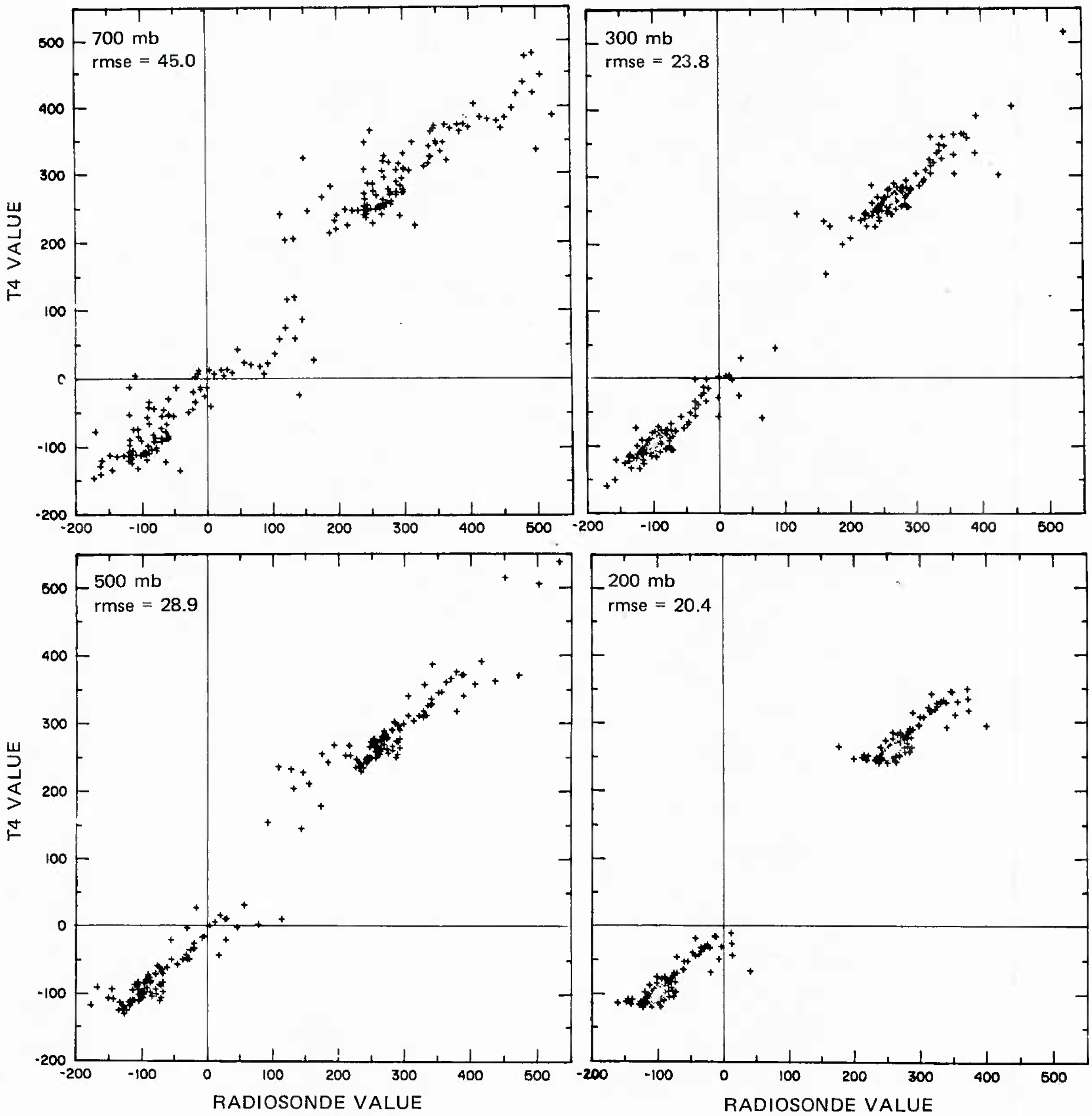


FIGURE 25 SCATTERGRAM SHOWING T4 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE III, 2 MAY 1979



(b) WIND DIRECTIONS — degrees

FIGURE 25 SCATTERGRAM SHOWING T4 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE III, 2 MAY 1979 (Concluded)

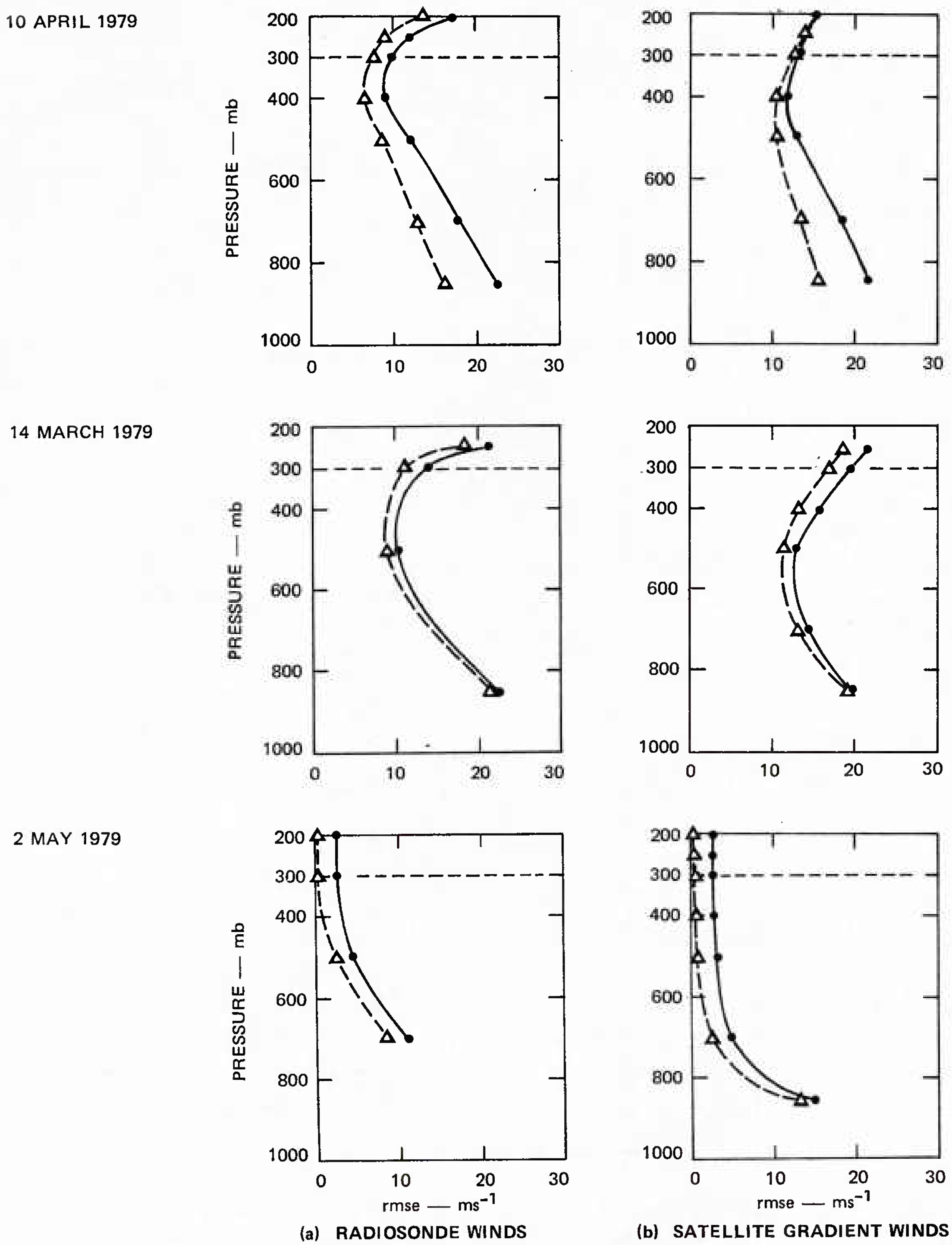


FIGURE 26 ROOT-MEAN-SQUARE ERROR PROFILES FOR CLOUD MOTIONS COMPARED WITH RADIOSONDE WINDS AND SATELLITE GRADIENT WINDS

Dashed lines show results obtained when cloud motions are first made nondivergent.

levels (solid lines in the left column of Figure 26). These rmse values were calculated at each level using the formula given in Eq. (6), but where $\mathbf{M}$ and $\mathbf{V}$ are now the analyzed cloud-motion vector and the analyzed radiosonde wind vector at some grid point. The summation is again made over N grid points, but the grid points used in this rmse calculations were those that fell within the areas that contained all three types of data (cloud motion, satellite temperature profile, and radiosonde).* The best fit (lowest rmse) for the first two test cases occurs at some level noticeably lower than the 300-mb level. In the 10 April case it appears to occur at, or slightly above 400 mb; and in the 14 March case between the 500- and 400-mb levels. The rmse curves for the 2 May case do not clearly depict any level of best fit, because the wind field was relatively similar at all levels above 500 mb.

Rmse profile values for the cloud motions were also calculated by comparing the cloud motions with the satellite gradient winds, rather than the radiosonde winds--the resulting rmse profiles are also shown in Figure 26 (solid lines in right column). The level of best fit now tends to occur somewhat lower: between 500 and 400 mb for the 10 April case and between 600 and 500 mb for the 14 March case.

The dashed lines in Figure 26 show the rmse that were obtained when the cloud motions were first made nondivergent. The effect was to decrease all the rmse values which is reasonable since a large part of the random error in the cloud-motion measurement is eliminated when the divergent component is eliminated. However, both the solid and dashed rmse curves give about the same result for the level of best fit.

The effects of applying the cloud motions to a level approximately 100-mb too high would be significant for the 10 April and 14 March cases. This is particularly true for technique T2, which does not have any control mechanism to ensure that the values are reasonable near the surface.

F. Modified Results For Test Case II: 14 March 1979

To illustrate the significance of the possible errors in the cloud-motion height assignment, a repeat calculation was made for Test Case II using technique T2. Test Case II was selected because it showed the greatest discrepancy between the height (300 mb) assigned to the cloud motions and the height of best fit (500 to 400 mb). Technique T2 was used because it would be more affected by incorrect cloud-motion heights than would T4. In the repeat calculation the following was performed:

* In the rmse calculations shown in Table 1, the grid points used were required to only lie within areas that contained satellite temperature profile data and radiosonde data.

- The cloud motions, originally assigned to 300 mb, were assumed instead to apply to both the 500- and 400-mb levels, because the best-fit level fell in between. Thus, nondivergent cloud-motion analyses were made for both of these levels using the same cloud motions but different gradient-wind first-guess fields.
- The wind fields below 500 mb and above 400 mb were then derived using the thermal wind to approximate the change of wind with height; that is technique T2 was applied below 500 mb and above 400 mb.

The graphical display of the wind fields obtained in this T2 calculation for Test Case II are shown in Figure 27. These results show a better agreement with the radiosonde analyses (Figure 15) than did the previous T2 analyses for this case (Figure 16), as would be expected. Scatter diagrams comparing the wind speeds and directions of this modified T2 analyses with those of the radiosonde analyses are shown in parts (a) and (b) of Figure 28. The scatter diagram results for Test Case II are comparable to those shown for T4 in Figure 24 although an improved agreement would also be achieved for T4 if reassigned cloud-motion heights were used in its application.

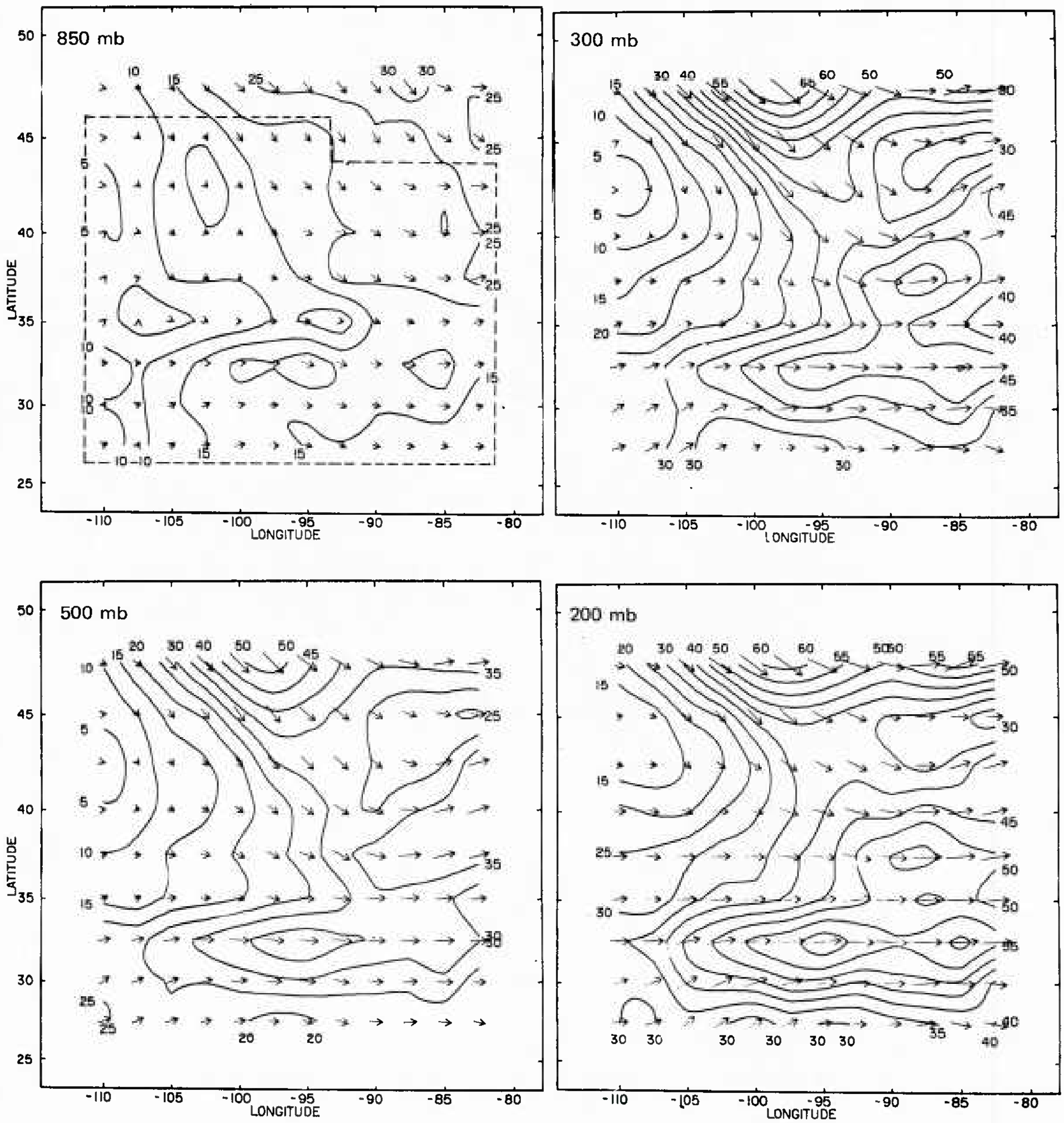


FIGURE 27 WIND FIELDS FOR 1000 GMT 14 MARCH 1979 DERIVED USING TECHNIQUE T2 AND MODIFIED CLOUD-MOTION HEIGHT ASSIGNMENT

Isotachs in ms^{-1}.

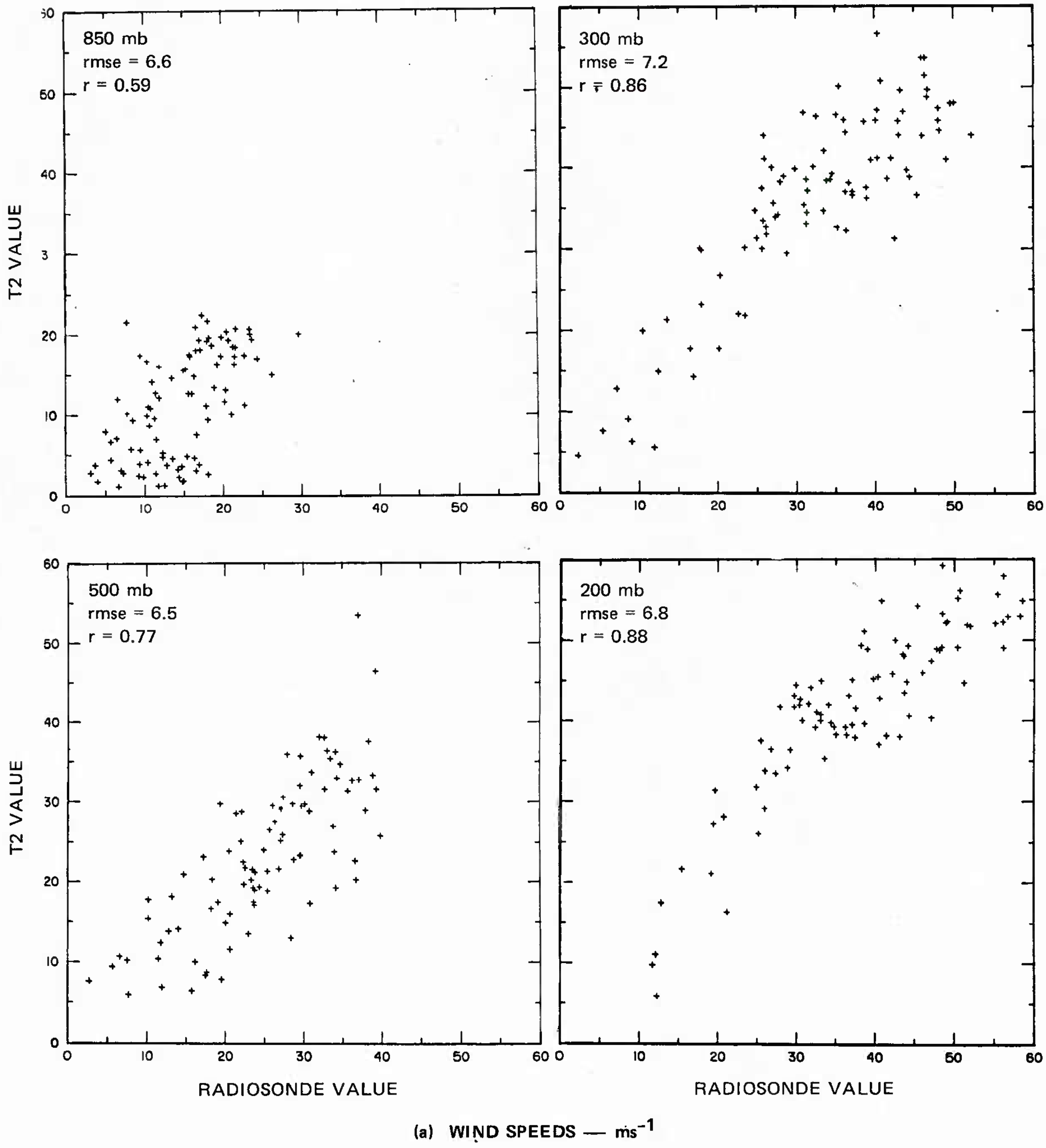
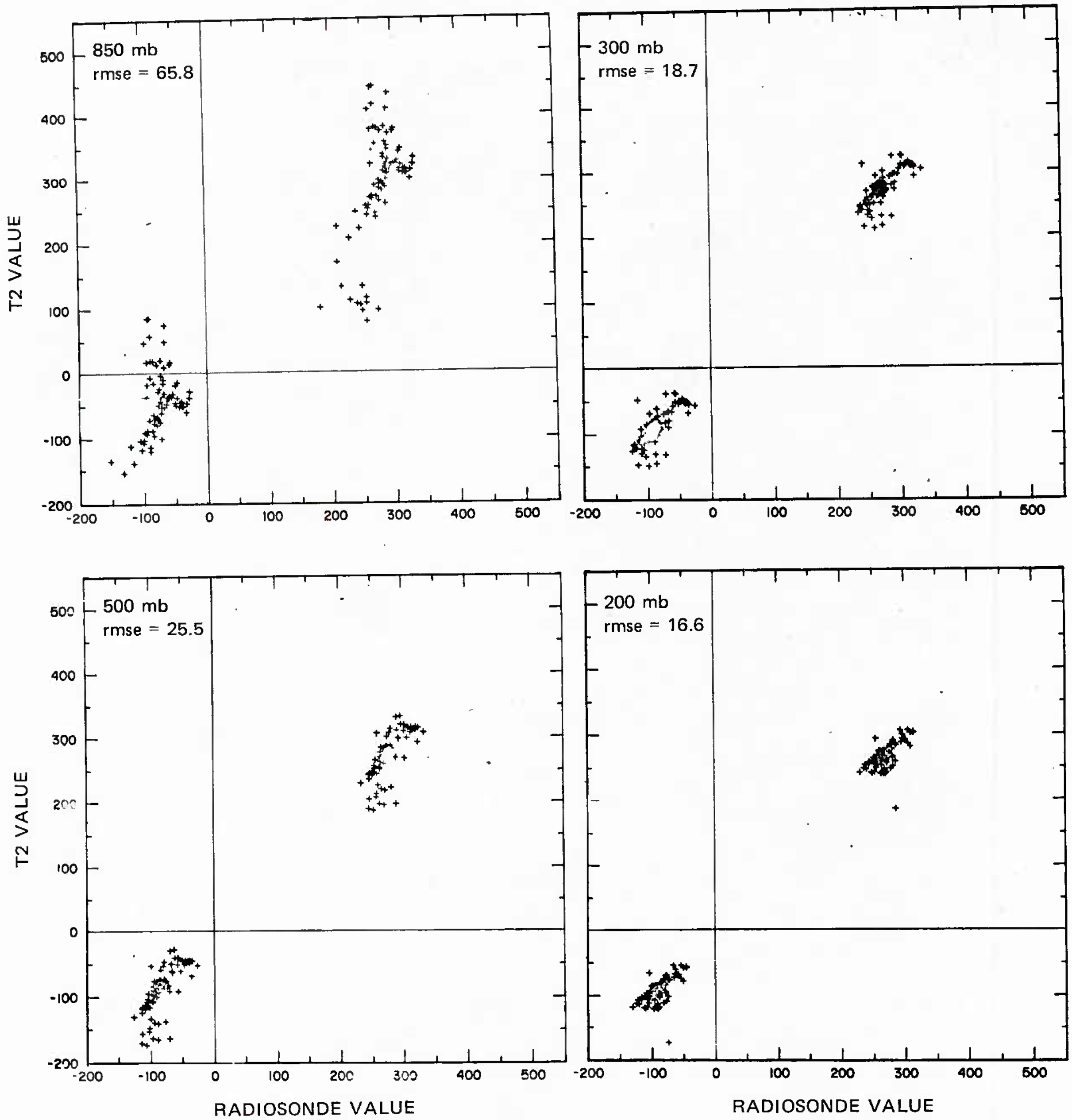


FIGURE 28 SCATTERGRAM SHOWING MODIFIED T2 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE II, 14 MARCH 1979



(b) WIND DIRECTIONS — degrees

FIGURE 28 SCATTERGRAM SHOWING MODIFIED T2 CALCULATED VALUES AS A FUNCTION OF RADIOSONDE VALUES FOR TEST CASE II, 14 MARCH 1979 (Concluded)

V SUMMARY AND CONCLUSIONS

In this study, four different techniques were tested for constructing wind profiles from satellite cloud-motion and temperature-profile data. The techniques were tested on three cases with TIROS-N temperature profile and GOES cloud-motion measurements. The four techniques are:

- T1--which is based on an attempt to locate the maximum wind level from the temperature structure characteristics. This technique was not successful because of the difficulty of accurately identifying the maximum wind level and because the cases did not have the classical features of jet streams upon which the concept was based.
- T2--which uses the thermal wind to build upward and downward from the cloud-motion level. This technique gave good results close to the cloud-motion level, but poorer results elsewhere, particularly near the surface.
- T3--which attempts to improve upon T2 by the introduction of the balance relationship. This technique gave some improvements in high-speed flow but did not result in any overall improvement over T2.
- T4--which is based on an eigenvector approach. This technique gave the best results principally because the surface geostrophic wind is used in its application--thus producing better results near the surface.

All the techniques gave definitely improved wind values at the cloud-motion level as compared with a geostrophic or gradient wind buildup from the surface. The differences between the calculated winds of the techniques and the radiosonde winds were caused by:

- Errors in the cloud-height estimates. These errors might be satisfactorily reduced by the use of more accurate algorithms based on satellite temperature sounding data or by the use of a cloud-motion level that gives the best fit with the satellite gradient wind profile.
- Errors and inconsistency in the satellite temperature-profile data. A combination of improved retrieval procedures and data editing should improve on the reliability and quality of these data.
- Differences between the geostrophic and actual winds. However, no significant improvement in the results was obtained by the use of the balance relationship.

- The errors of radiosonde data and the inconsistency between the spatial representatives of satellite temperature data and of radiosonde temperature data. These types of problems present basic limitations upon the techniques which can only be partially removed by smoothing.

Although the errors associated with the techniques are greater than would be desired, the results from this study are promising, particularly for application to data-sparse regions and for studying the detailed evolution of events using geosynchronous-type satellite data. Further investigations that would be of value are:

- Refinement of techniques T2 and T4. Technique T2, which has the advantage of being simpler, should be tested using surface data to permit a better comparison with T4. Technique T4 has the advantage that it can be applied directly to each cloud-motion measurement for deriving wind profiles at that point. (These profiles could then be analyzed onto the three-dimensional mesh.)
- Use of the geostationary VAS satellite data. This satellite is now in operation and will be providing continuous temperature sounding data for the global area within its view. Combined TIROS-N and VAS data sets, which should be available in the near future, will provide a good basis for further testing of the techniques.
- Use of additional data types, such as the recent high-quality automated aircraft reports, constant-level balloon measurements, and SEASAT winds. The SEASAT winds would be particularly valuable, since they would provide surface values over oceanic areas for use in calculating wind profiles. Some SEASAT data are available that may coincide with available temperature sounding data, so that this idea could be tested.
- Testing the techniques over tropical areas. In the equatorial zones, the geostrophic and thermal-wind approximations are not generally valid; however, they may still present a suitable guide for interpolating between a surface wind and a cloud motion. The winter MONEX data for the Malaysia area could provide cases for study.
- Testing other types of techniques, possibly based on statistical profile relationships similar to that attempted in technique T1. Use of eigenvectors would probably be useful in such an attempt, since the number of variables between which relationships would need to be derived could be significantly reduced. This type of investigation would require processing of large amounts of data.

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Appendix A

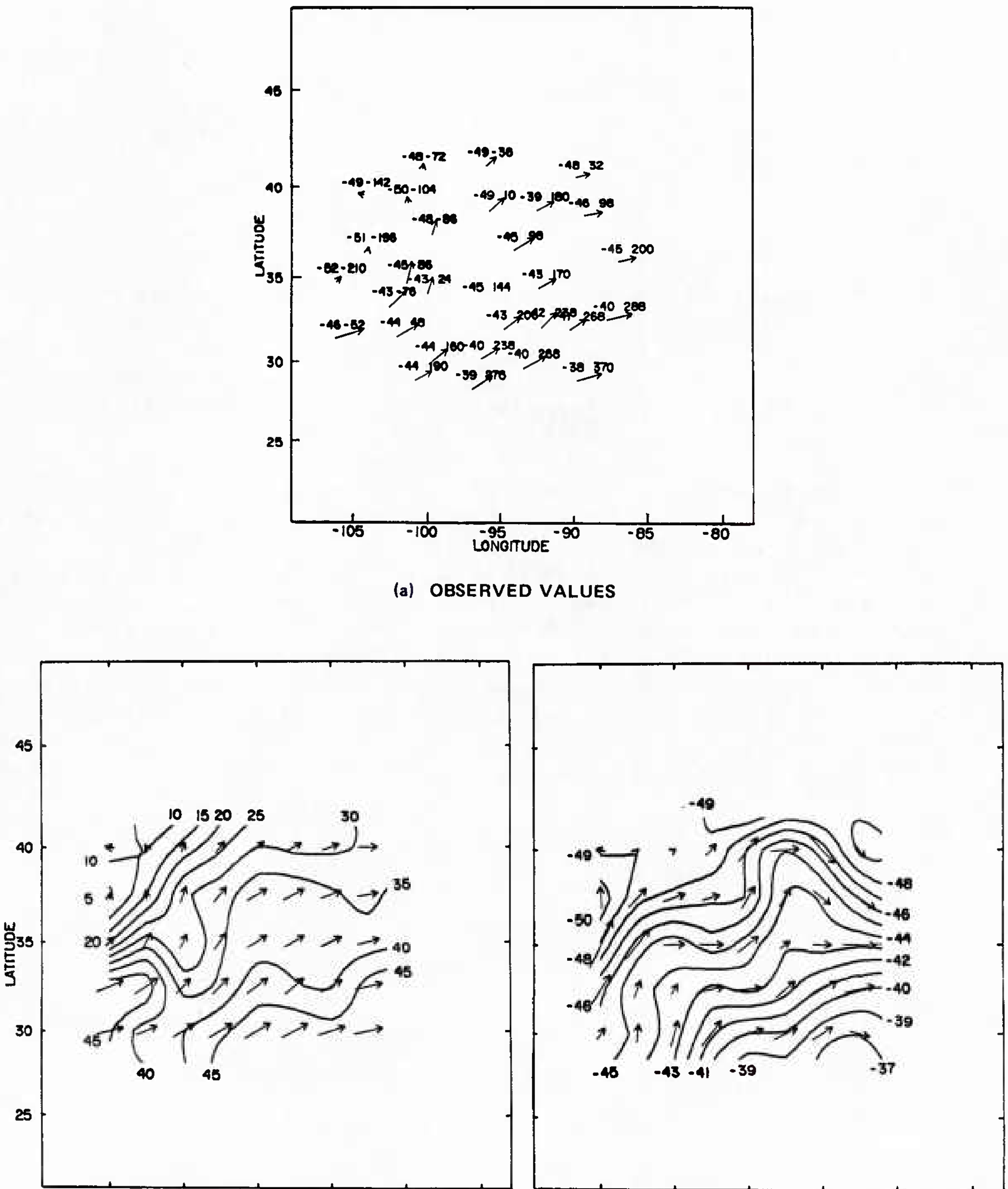
ANALYSES FOR 2000 GMT 10 APRIL 1979 BASED ON AVE RADIOSONDE DATA

Appendix A

ANALYSES FOR 2000 GMT 10 APRIL 1979 BASED ON AVE RADIOSONDE DATA

AVE radiosonde data at 300 mb for 2000 GMT 10 April 1979 are shown in Figure A-1(a). These data much more densely spaced than the standard radiosonde data, are for the same time as the satellite data of Test Case I. Wind and temperature/thermal-wind analyses of these data are shown in Figure A-1 (b) and (c). These analyses may be compared with those made for the standard data [see Figures 4(c), 5(c), and 6(b) of text].

Although the AVE data analyses show more detail, they are basically consistent with those based on the standard observations, and the time interpolation procedure used in the study to produce the 2000 GMT analyses [such as Figure 5(c)] appears to be justified. The differences between satellite and radiosonde analyses would, therefore, have to be attributable to either the current inaccuracies of satellite-data or the inconsistencies between the two types of measurement; that is, a radiosonde temperature measurement is essentially for a point location, but a satellite measurement is for a large volume of both considerable vertical thickness and horizontal size.



(a) OBSERVED VALUES

(b) WIND ANALYSES

(c) TEMPERATURE ANALYSES

FIGURE A-1 AVE WIND AND TEMPERATURE VALUES AT 300mb FOR 2000 GMT 10 APRIL 1979

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