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OBJECTIVE AND DYNAMIC ANALYSES OF TROPICAL WEATHER

FINAL REPORT

By

R. L. Mancuso *R. M. Endlich*

June 1970

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FINAL REPORT

18 MARCH 1968 TO 17 MARCH 1970

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Prepared by

R. L. MANCUSO R. M. ENDLICH

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA 94025

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ABSTRACT

Studies concerned with computer methods of analyzing and forecasting tropical weather patterns are summarized. The numerical techniques include a method of making grid-point analyses of winds, a method of balancing divergence fields in the vertical, a procedure for adjusting wind fields to "fit" cloud patterns, and a tropical forecasting model. Previously, these techniques were applied to synoptic scale analyses in the Caribbean. In this report, they are used to make mesoscale analyses of relatively dense data obtained by the Army in South Vietnam. For the month of September 1967, mean winds in four layers between the surface and 10 km were calculated for the hours 0300, 0900, 1500, and 2100 LST at each station. Objective analyses of these data on a one-quarter-degree latitude-longitude grid show the diurnal wind patterns associated with sea breezes and topographic effects. The variations in the mesoscale divergence fields in the boundary layer are particularly prominent. For this particular region, computed fields of divergence and vorticity in the boundary layer do not show any correlation, contrary to the experience of several other investigators for other tropical areas. Experimental short-range forecasts were made from the objective analyses, and appeared to be computationally satisfactory; however, the model was not able to include the diurnal effects. As a result of this work, we conclude that the most promising avenues for making significant progress in tropical forecasting depend upon use of new, high-density data (such as cloud motions and development shown by synchronous satellites),

computer methods of analyzing and synthesizing different kinds of information, and further refinement of numerical models that include convection and low-level effects related to heating and topography.

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I INTRODUCTION

This study has been concerned with computer methods of analyzing weather patterns in the tropics, and of prediciting their behavior for periods up to a day in advance. The problems are more difficult than in midlatitudes, since the tropical weather patterns generally have weaker flow speeds, and are heavily influenced by local topography and by changing patterns of heating and cooling throughout the day. Vertical convection is an important process, and is of a smaller scale in space and time than the familiar cyclonic distrubances of midlatitudes. There is a great need for objective methods, since subjective techniques are slow and tedious, and do not necessarily provide forecasts that are adequate in regard to either timeliness or accuracy.

All the work reported herein is based on objective meteorological analyses. The normal tropical practice of relying upon wind data rather than pressure-height and temperature observations has been followed (Riehl, 1954). The kinematic properties (i.e., divergence and vorticity) of the objective wind analyses have been observed to be within the bounds found by others using subjective techniques (e.g., Fujita et al., 1969).* The wind analyses are portrayed as maps of wind vectors centered on grid points. These displays are generated on a computer-controlled cathode ray tube. A set of isolines for a scalar quantity (such as wind speed, vorticity, or divergence) is sometimes included. The smoothness of the isolines depends upon the amount of storage and computation time that is employed--i.e., smooth lines are somewhat more costly than jagged lines. Numerous examples of wind vectors and isolines are given later.

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*References are listed at the end of this report.

Studies were made of meteorological conditions in the Caribbean and in Southeast Asia. The Caribbean is a fairly large region with an irregular network of rawinsonde stations that nevertheless permits one to resolve most synoptic-scale weather patterns. Concurrent satellite cloud features for the same situations were viewed and compared with analyzed quantities. In contrast, South Vietnam is a relatively small region (Figure 1) where 10 to 15 U.S. Army Artillery rawinsonde units have taken several soundings per day. These latter data were gathered and processed under the direction of the Atmospheric Sciences Laboratory, Fort Monmouth, N.J. We have used them to analyze the mesoscale flow features over South Vietnam, as discussed in Sections III and IV below. Also, a multilayer numerical forecasting model was formulated during the study. It is based primarily on the three-dimensional advection of vorticity and divergence, as described in Section II.

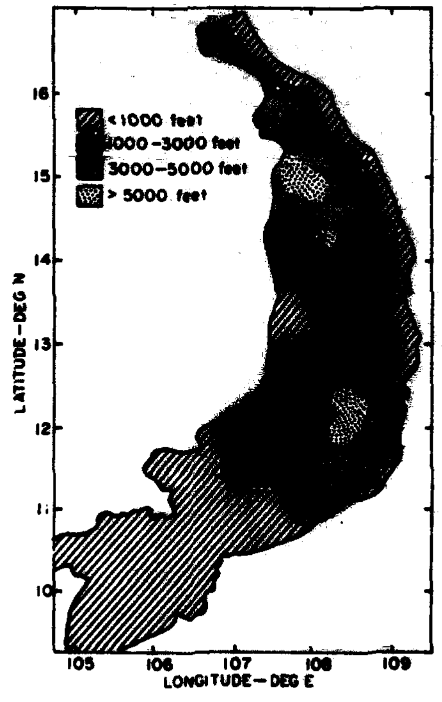


FIGURE 1 MAP OF SOUTH VIETNAM SHOWING PRINCIPAL TOPOGRAPHIC FEATURES

II BRIEF REVIEW OF THE CONTRACTUAL WORK

A. Objective Analysis Techniques

To provide an overview of the work, studies that were reported upon in the previous Semiannual Reports 1, 2, and 3 (November 1968, April 1969, and November 1969) are summarized below.

The objective analysis of tropical wind observations is of basic importance. Analyses were made for a selected number of vertical layers. For each rawinsonde report, the average u and v wind components in each layer were computed. Next, grid point values of u and v were determined for selected grid spacings. At each grid point the value of u or v was determined by a first-degree polynomial least-squares fit to the five nearest observations. In order to avoid excessive smoothing and to make the analyzed grid-point values agree most closely with the values at the nearest station, an observation was assigned a weight inversely dependent on its distance from the grid point. Also, observations upwind or downwind from a grid point were given more weight than crosswind observations. This effect tended to align the isopleths of the analyzed quantity in the flow direction. Each grid point was also assigned an initial-guess value that was included in the computation with a relatively low weight. In sparse-data areas this initial guess is important in establishing the final grid-point value, whereas in other areas it has little influence. At present, a weighted average of the five nearest observations is used to provide the initial guess, but an analysis based on satellite data or a forecast field could also be used. A considerable amount of experience with this method shows that it gives very reasonable results. An example of station winds in the first kilometer above the surface is shown in Figure 2(a), and the corresponding objective analysis is shown

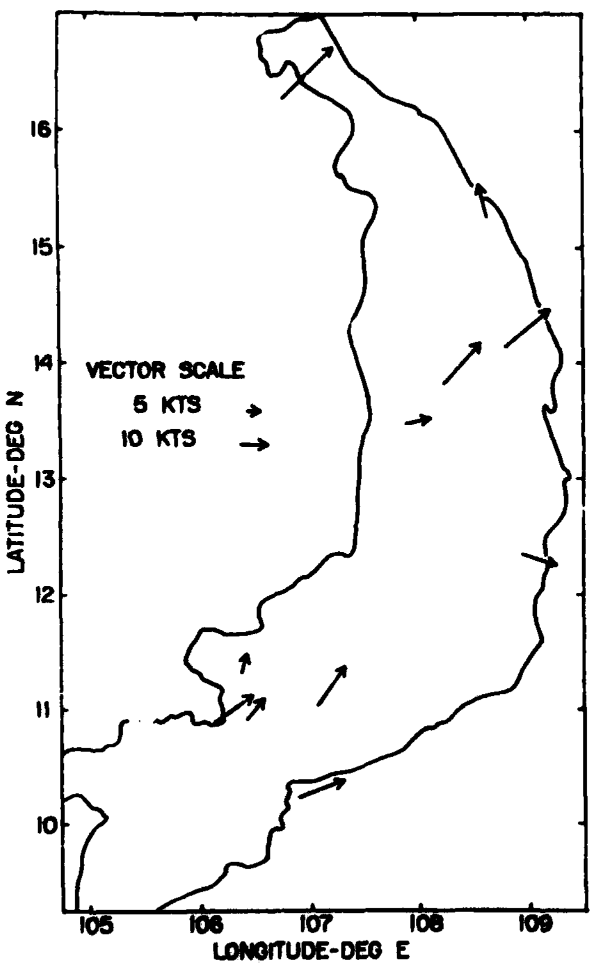


FIGURE 2a TYPICAL OBSERVED WINDS IN THE SURFACE-TO-1-km LAYER OVER SOUTH VIETNAM. These data are for 2100 LST 7 July 1967

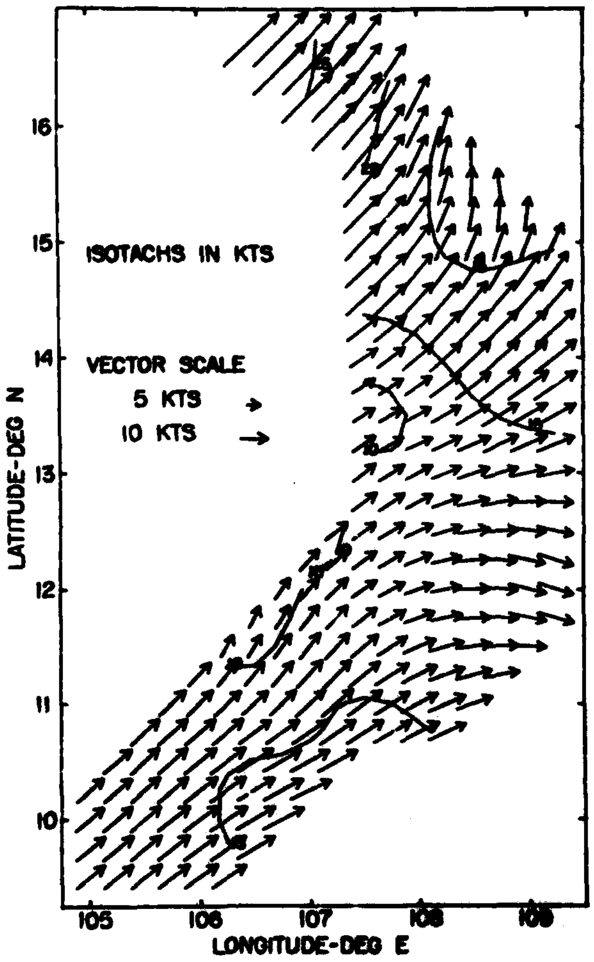


FIGURE 2b OBJECTIVE ANALYSIS OF THE OBSERVED WIND VECTORS, WITH ISOTACHS IN KNOTS. The map is made by a cathode-ray-tube display system

in Figure 2(b). The objective analysis tends to fit isolated reports quite closely, and to perform some smoothing in areas having the most dense data. Programs are also available for computing values of stream function, velocity potential, and balanced heights, all in accord with the wind analyses (see Mancuso, 1967). The balanced heights are determined from the usual form of the balance equation.

Experiments were also carried out to introduce satellite data into the analyses. This was done in two ways. In the first approach, cloud motions determined from ATS-I synchronous satellite picture sequences were introduced as "winds." In regions where rawinsonde data were also available, the agreement between cloud motions and measured winds appeared to be fairly good. Such cloud motions may be most useful in areas devoid of other data. The main difficulty at present is the lack of information on cloud heights, which prevents one from assigning a cloud motion to a definite altitude. In the second approach involving cloud data, it is assumed that an analyst can inspect single cloud photographs (for example, as obtained by polar orbiting satellites) and can estimate wind directions from the orientation of cloud features. If this is true, and boundary values of wind direction and speed are known, a complete wind-speed field consistent with the internal wind directions and the boundary values can be computed. The mathematical development and a computer program for this purpose were described in Semiannual Report 1, and will be published soon (Mancuso, 1970).

B. Balancing the Divergence Field Vertically

In order to have a tropical analysis that is meaningful in regard to clouds and weather, one must determine the horizontal divergence field in each layer with a reasonable degree of accuracy. This is very difficult to achieve. One physical constraint on divergence is that the vertically integrated value must be close to zero. This statement is based on the pressure-tendency equation, and has been used previously by Pfeffer (1962). We used this principle in adjusting the divergence values in each vertical column so that the surface-pressure tendency would be zero at the initial analysis time. Corrections to the originally analyzed divergence values were computed in a manner that allows larger corrections in the higher layers where wind analyses are more uncertain. Formulas for making these corrections were given in Semiannual Report 2. Then vertical motions consistent with the corrected divergence fields were computed from the continuity equation, and used in vertical advection.

C. Adjusting Wind Fields to Fit Cloud Patterns

Frictional drag in the atmospheric boundary layer tends to produce inflow (convergence) in cyclonic circulations, and outflow (divergence) in anticyclonic circulations in the tropics (Charney and Eliassen, 1964). Observational studies by Lateef (1967) and Gray (1968) associate major cloudy areas with positive relative vorticity and convergence in the lower atmosphere, and clear areas with the opposite conditions. From these relationships, one may infer that tropical wind analyses, which are invariably based on insufficient data of standard types, can be improved by causing them to have relatively large vorticity and convergence in cloudy areas. (Such areas are of course depicted in excellent detail by satellite photography.) A test of this concept was reported in Semiannual Report 3, using a paper by Fujita et al. (1969) as a standard for comparison. These authors made a subjective analysis of cloud-motion vectors shown by the ATS-I satellite, and adjusted the flow pattern to fit the clouds so as to produce the relationships described above. In our experiment, an analogous objective analysis was made and then modified using the method of "direct" or "vector" alterations (Endlich, 1967) to produce the desired correspondence of kinematic quantities and clouds. It was found that the adjusted objective analysis was very similar to the careful hand analysis of Fujita et al. Therefore, it appears that if reliable relationships between cloud patterns and kinematic quantities can be established, the satellite cloud photographs can be used to improve analyses based initially on other data. Since the ATS cloud photographs give continuous coverage over much of the globe, the potential benefits from using them systematically in this manner are believed to be very significant.

D. A Tropical Forecasting Model

This numerical model has been retained in the form described in Semiannual Report 2. In outline, it is based on the three-dimensional advection of absolute vorticity and of divergence. The horizontal Eulerian advection is performed using an alternating-direction implicit (ADI) method based upon a combined upwind-centered difference operator (Endlich, 1970). Alternatively, one can use a Lagrangian technique described in the Appendix. These two advection techniques seem to give very similar results. The model includes a vorticity production term. In accord with the reasoning given in Section II-C, surface frictional drag is simulated in the lowest layer by introducing convergence in cyclonic flow and divergence in anticyclonic flow. Latent heat release is parameterized in areas analyzed as having rising motion, by augmenting the divergence in proportion to the vertical motion multiplied by an altitude parameter. The latter decreases linearly with height to reflect decreasing moisture aloft. After each time step, divergence is rebalanced vertically, using the technique described in Section II-B. Then the pre-existing winds in each layer are adjusted to fit the forecast vorticity and divergence using the method of vector alterations.

The model was used to make some twelve-hour forecasts using Caribbean data. It was formulated for four vertical layers and a 2.5-degree latitude-longitude grid. Time steps as long as two hours are made possible by the ADI formulation of advection. The forecasts were well behaved computationally. However, the rms vector changes in observed winds in 12 hours were only in the range from 3 to 5 m s^{-1}. These changes are only moderately larger than rms errors of measuring winds; therefore it is difficult to separate real changes from random errors. It follows that validation of tropical forecasting models is very difficult. Different initial divergence fields were used to test the sensivity of the model under otherwise similar conditions, and it was found that considerably different forecasts resulted. This is believed to be a desirable characteristic; however, it implies that the initial divergence field must be known quite accurately if one is to obtain tropical numerical forecasts of useful precision.

III DIURNAL CHANGES IN MESOSCALE FLOW PATTERNS OVER SOUTH VIETNAM IN SEPTEMBER 1967

In Southeast Asia, synoptic weather patterns are largely controlled by monsoonal circulations that consist generally of southwesterly winds in summer and northeasterlies in winter (Schutz, 1967). Smaller-scale weather processes are related to the topography (Figure 1) and to diurnal influences. However, the details of the mesoscale motions are not well known here, or in most other parts of the tropics, due to a lack of data. In recent years, a considerable amount of rawinsonde data has been taken in South Vietnam by the U.S. Army at about twenty different station locations. The spacing between stations is relatively close, and most of them take four soundings per day. The number of rawinsonde reports available at a given analysis time varies between 10 and 15. The purposes of this section are to analyze mesoscale flow patterns in this region, to depict diurnal cycles and topographic effects, and to calculate the magnitudes and interrelationships of divergence and vorticity.

During the month of September 1967, the rawinsonde data for South Vietnam were relatively complete in their spatial and temporal coverage. Therefore, these data were selected for initial analysis. In order to view the prevalent diurnal variations in the flow patterns, the average wind fields for September were constructed for four altitude layers (0 to 1 km, 1 to 3 km, 3 to 6 km, and 6 to 10 km above the surface), for four daily times (0300, 0900, 1500, and 2100 LST), and an overall mean. The original rawinsonde cards consisted of eleven wind reports for thinner layers. These data had been transcribed from written records, key punched, and checked at the National Weather

Records Center using criteria specified by Mr. Marvin Lowenthal. About 50 percent of all the observations fell within one hour of the chosen analyses times and about 90 percent of them within two hours. If no observation was available for a particular station, then values were quadratically or linearly interpolated, provided that sufficient observations were available over a 30-hour span. Mean monthly values of u and v wind components for the four times and four layers were first computed for each of the stations. The mean station wind values were then objectively analyzed using the least-squares method described in Section II-A. The spherical grid increment was set at 1/4 degree of latitude and longitude in order to preserve the smallest details that can be analyzed from these observations. The divergence and vorticity fields were computed from the analyzed mean wind fields using standard formulas. They actually apply to layers at constant heights above terrain, as described earlier. Computations made for some individual times showed that these vorticity and divergence values were very similar to those that resulted when the winds were analyzed at a constant height above sea level. The divergence fields were vertically balanced in a manner described in Section II-B, and the wind fields were then readjusted to fit the balanced divergence fields. These readjustments of the wind fields were relatively small.

The mean winds for the month of September and the associated divergence fields for the lowest layer are shown in Figure 3 for the hours 0300, 0900, 1500, and 2100 LST. In addition, the overall mean winds and divergence and the same mean winds and the associated absolute vorticity are shown. The general wind field in this layer appears to be fairly constant throughout the day; however, the center of convergence on the northeast coast intensifies and moves southward during the daylight hours. This change is due predominantly to the growth of a sea-breeze circulation that reaches its maximum near 1500 LST.

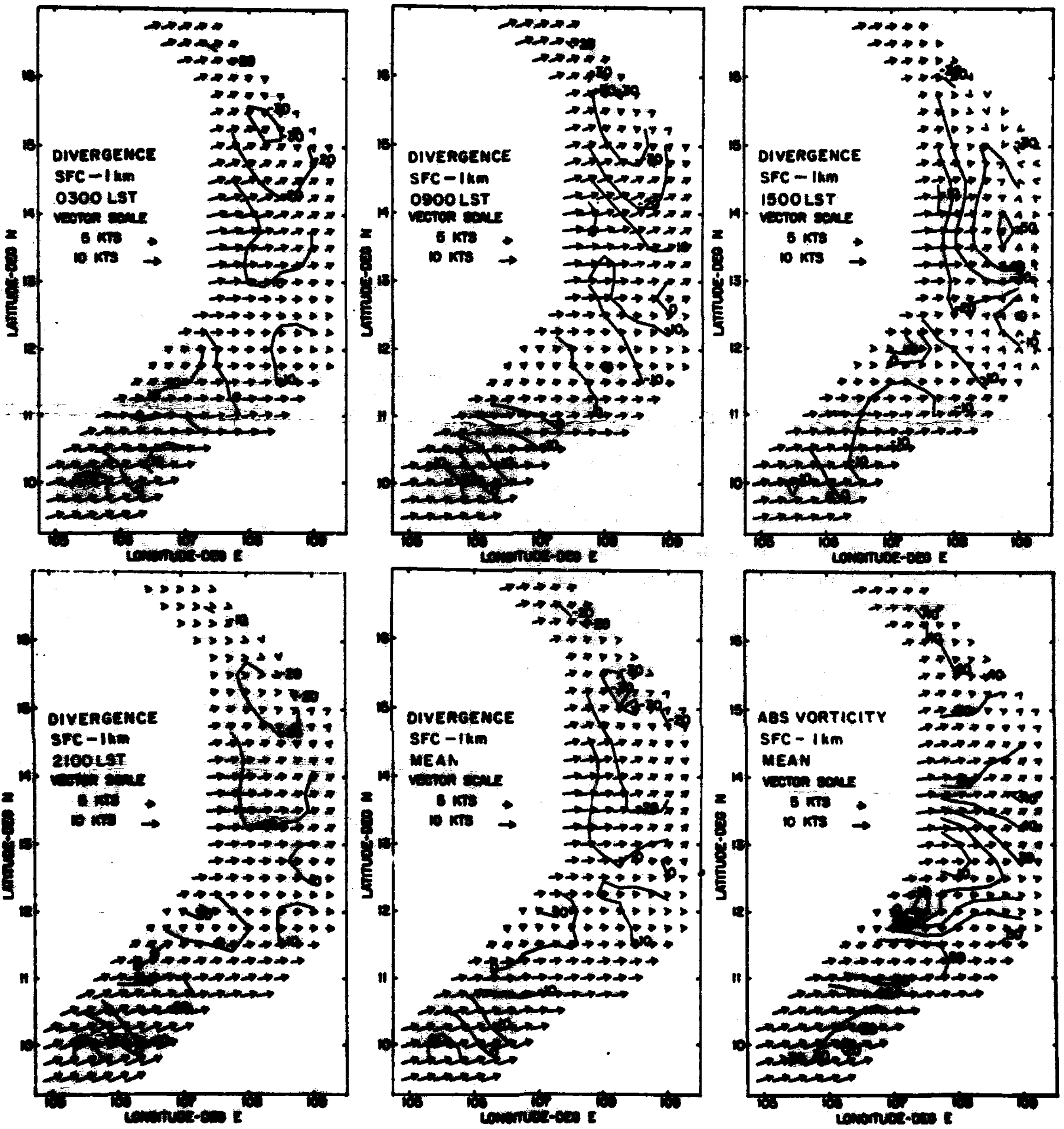


FIGURE 3 MEAN WINDS FOR SEPTEMBER 1967 IN THE SURFACE-TO-1-km LAYER AT FOUR DIFFERENT HOURS, AND FOR ALL HOURS COMBINED. The isolines are for divergence or absolute vorticity, as indicated, in units of $10^{-6}\ s^{-1}$

It can be seen that the sea breeze is most pronounced between 12°N and 16°N, in the lee of the major mountain barriers. The mean sea breeze is probably produced by the heating patterns and friction of this particular terrain (see Figure 1). Diurnal changes are small over the southern portion of the country. The mean divergence field has centers of convergence near 15.5°N and 10.5°N. It is suggested that the diurnal changes in the divergence field (which can be easily computed as differences between the various analyses of Figure 3) might provide a basis for parameterizing the influences of heating and topography ~~(during a certain season)~~ for inclusion in a mesoscale forecasting model for this area.

In the second layer (1 to 3 km), the mean flow consists of rather uniform westerlies, with fairly weak divergence patterns (Figure 4). Diurnal changes are relatively small. In the third layer (3 to 6 km), wind speeds reach a minimum over the southern half of the country (Figure 5). Weak divergence tends to predominate in those areas where the low-level flow was convergent. The mean flow in the fourth layer (6 to 10 km) is shown in Figure 6. In contrast to the lower layers, it has easterly winds. The most pronounced features of the average divergence field in Layer 4 are centers of divergence at 10.5°N and 15.5°N; these approximately overlie centers of convergence in the lowest layer. It is interesting also to compare the mean absolute vorticity fields in the four layers (Figures 3 to 6). These show a marked tendency for a vertical consistency of vorticity that is rather surprising in view of the different basic flow speeds and directions in the layers.

Statistics concerning the divergence and relative vorticity of the mean flow, and the correlation between them are given in Table I. The magnitudes are believed to be reasonable for this scale of analysis.

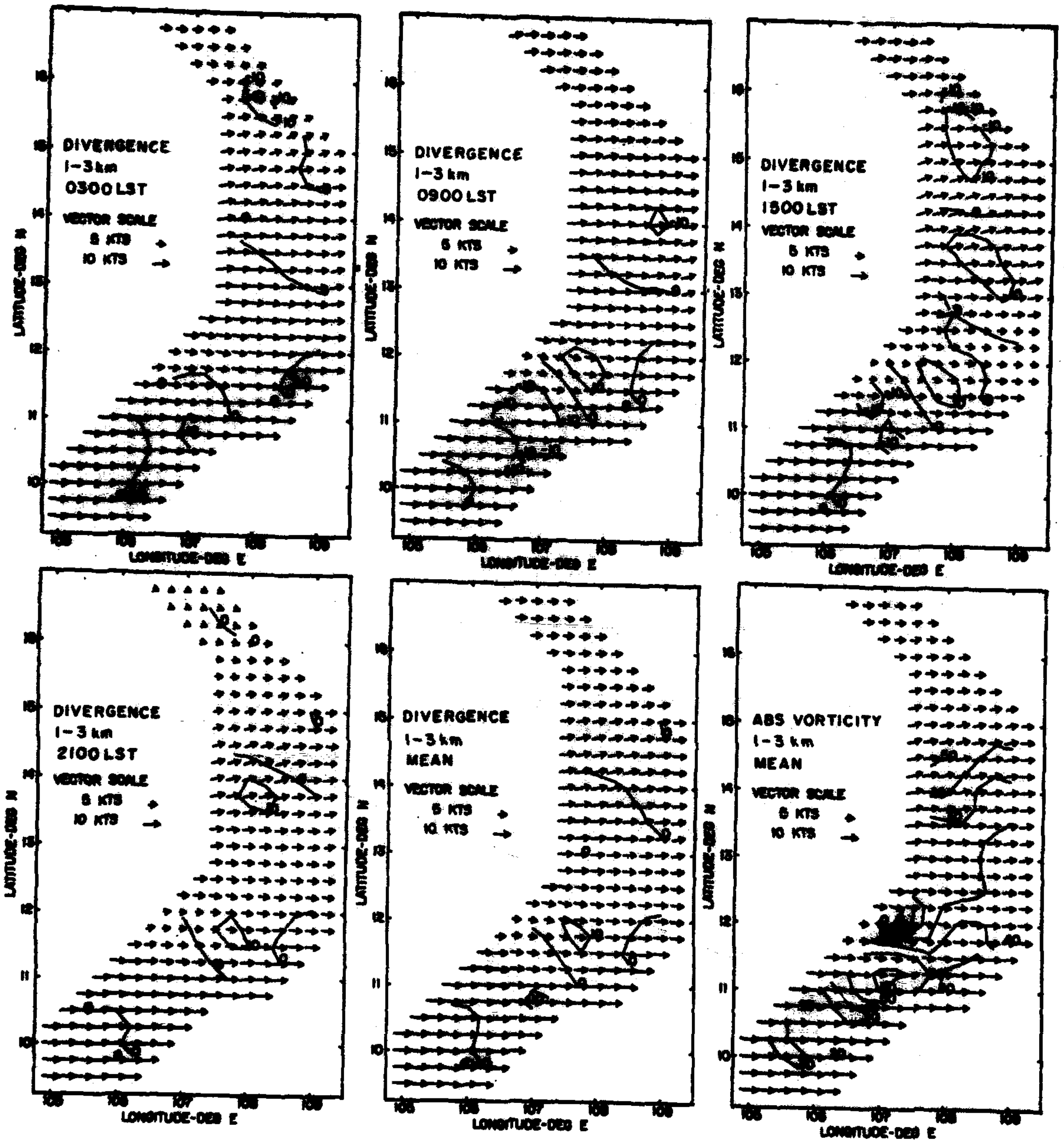


FIGURE 4 MEAN WINDS FOR SEPTEMBER 1967 IN THE 1-TO-3-km LAYER AT FOUR DIFFERENT HOURS, AND FOR ALL HOURS COMBINED. The isolines are for divergence or absolute vorticity, as indicated, in units of $10^{-6}\ s^{-1}$

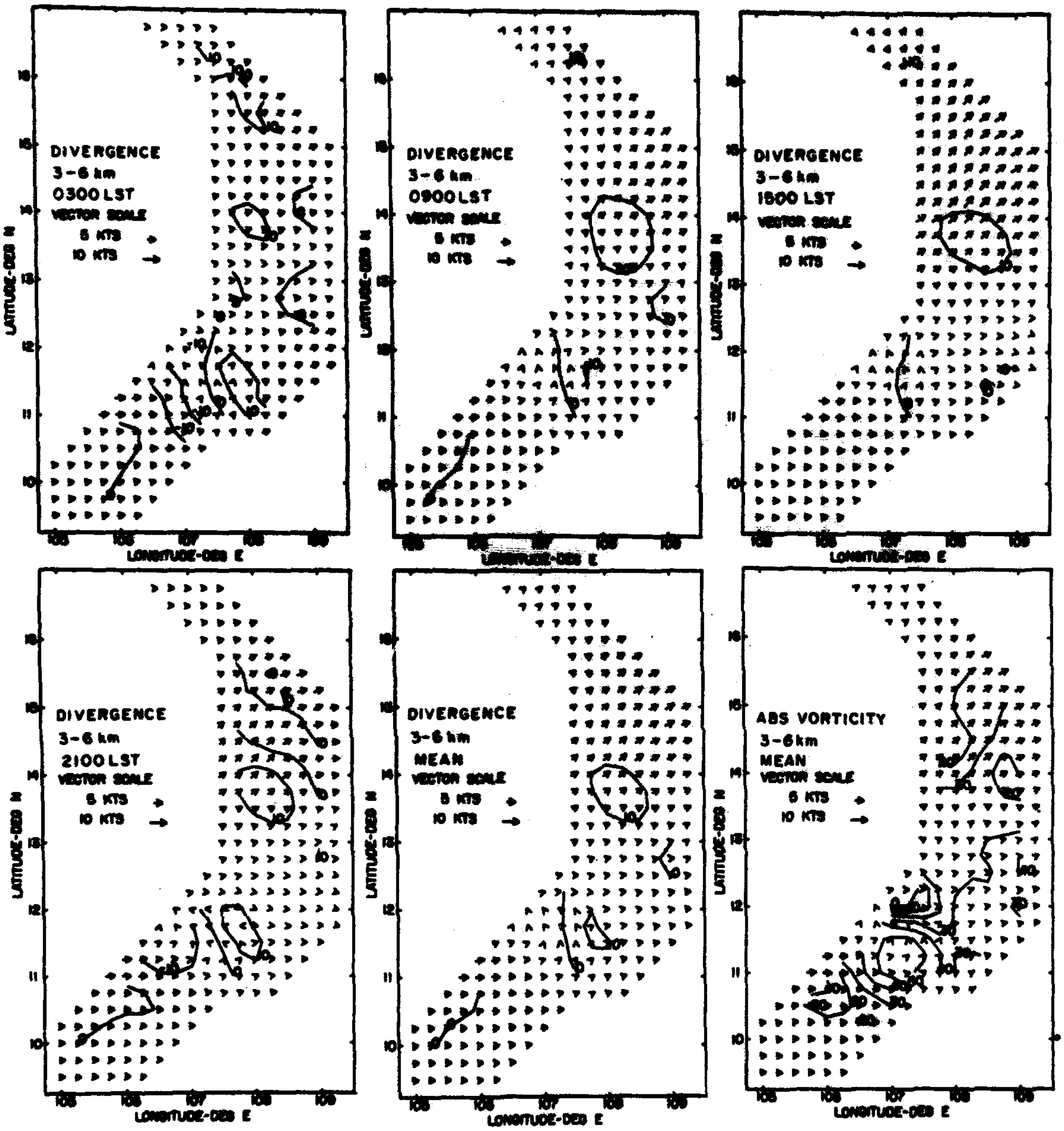


FIGURE 5 MEAN WINDS FOR SEPTEMBER 1967 IN THE 3-TO-6-km LAYER AT FOUR DIFFERENT HOURS, AND FOR ALL HOURS COMBINED. The isolines are for divergence or absolute vorticity, as indicated, in units of $10^{-6}\ s^{-1}$

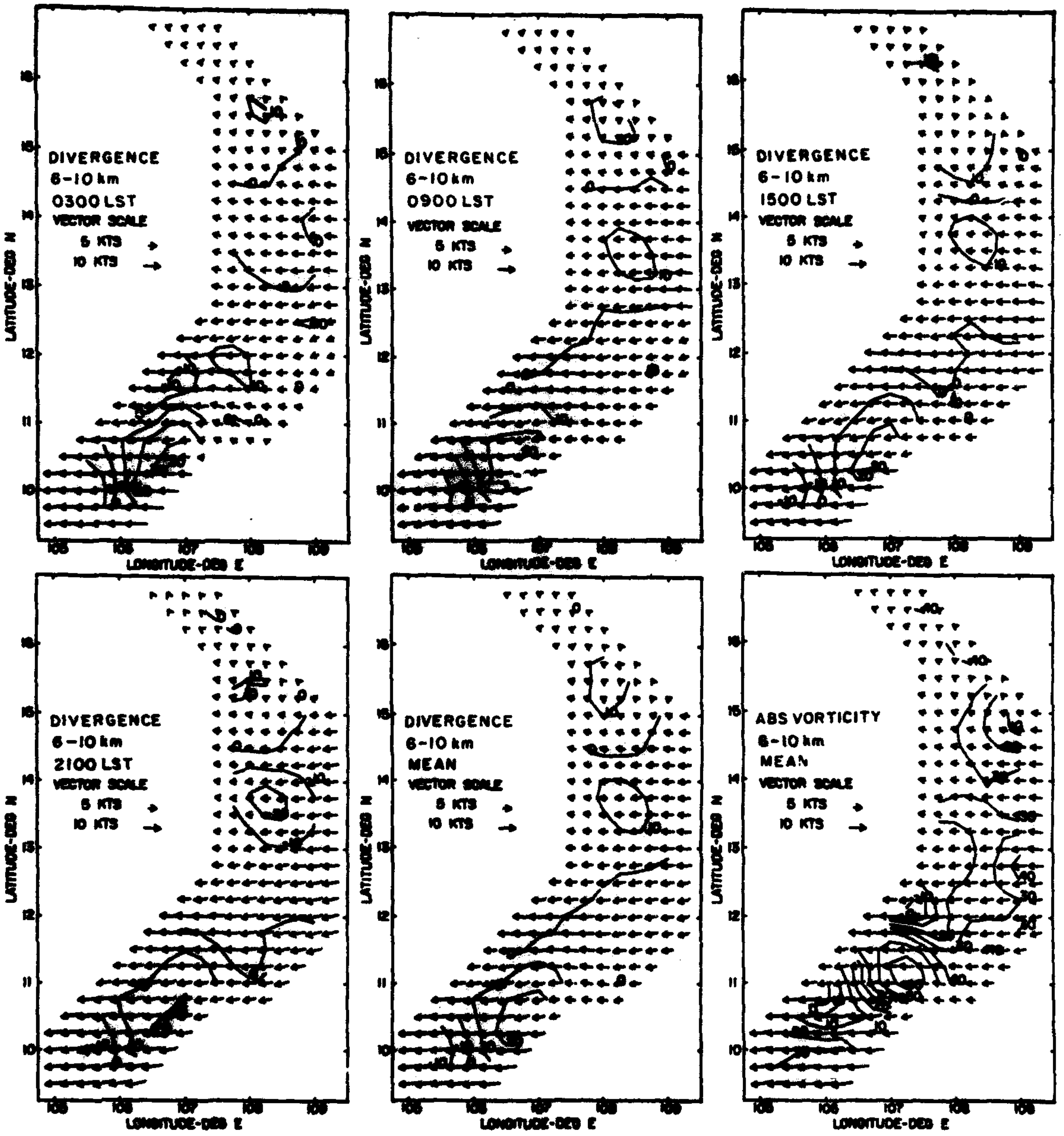


FIGURE 6 MEAN WINDS FOR SEPTEMBER 1967 IN THE 6-TO-10-km LAYER AT FOUR DIFFERENT HOURS, AND FOR ALL HOURS COMBINED. The isolines are for divergence or absolute vorticity, as indicated, in units of $10^{-6}\ s^{-1}$

Table I

THE MEAN VALUES, STANDARD DEVIATIONS, MEAN MAGNITUDES AND CORRELATIONS OF DIVERGENCE (D) AND RELATIVE VORTICITY (ζ) IN FOUR LAYERS OVER SOUTH VIETNAM, SEPTEMBER 1967

Altitude above Surface	Divergence (10^{-6} s^{-1})			Relative Vorticity (10^{-6} s^{-1})			Correlation between ζ and D
	Mean Value	Standard Deviation	Mean Magnitude	Mean Value	Standard Deviation	Mean Magnitude	
0-1 km	-11	10	12	6	15	14	-0.01
1-3	0	5	5	5	12	10	-0.45
3-6	3	5	5	0	11	8	-0.32
6-10	3	8	7	-5	15	12	0.14

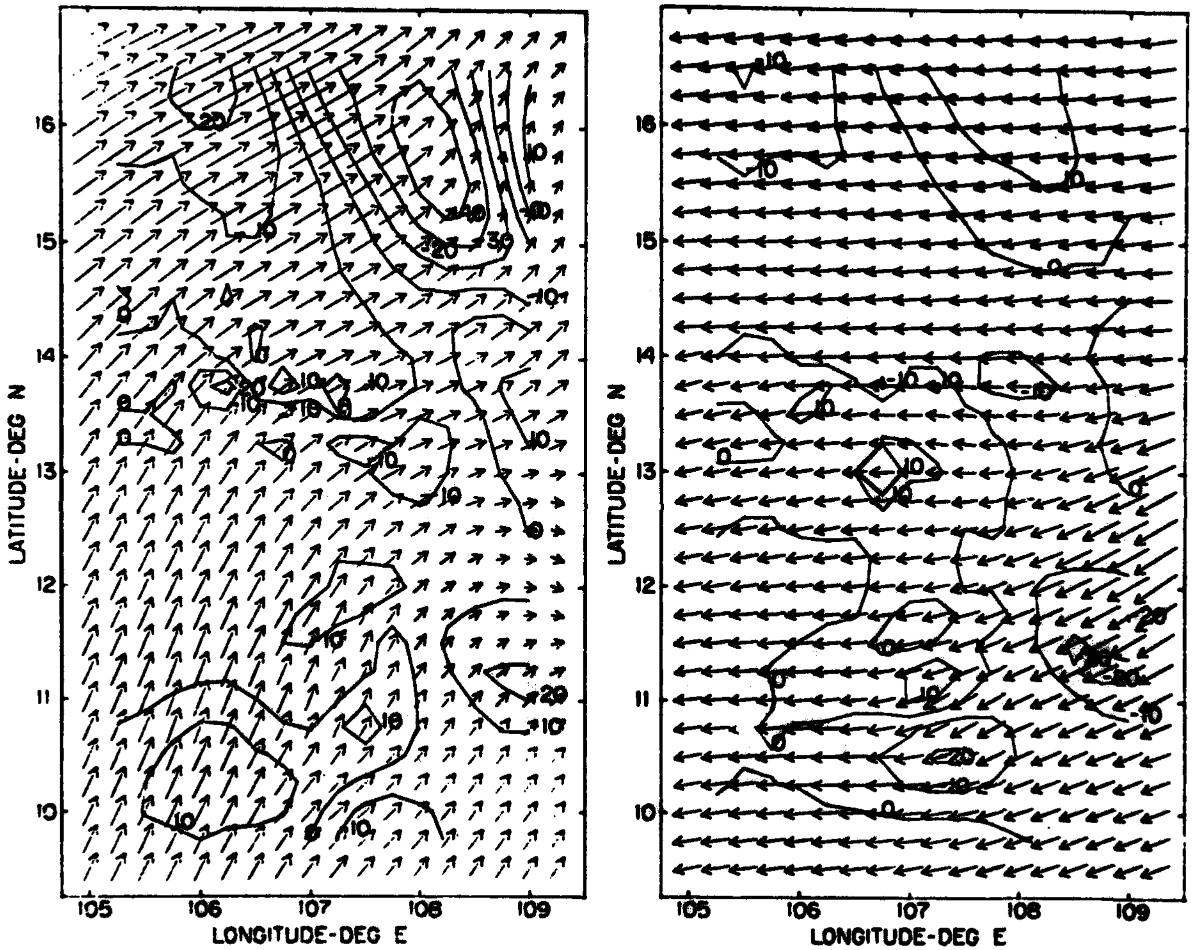
In the lowest layer, there is net convergence over South Vietnam giving way to divergence aloft. Magnitudes of divergence are on the average about 0.7 times as large as the magnitudes of vorticity. This is in contrast to midlatitude conditions where the ratio is normally considerably smaller than this. Correlations between divergence and vorticity are near zero, except in the 1 to 3-km layer, where the correlation is negative, as one might expect, but still not of particularly significant size. The lack of correspondence between convergence and positive relative vorticity in the lowest layer indicates that the mechanism of frictional inflow in cyclonic vortices apparently is not predominant in the mean over this particular land area.

In summary, analyses of averaged winds over South Vietnam for September 1967 show that the sea breeze is clearly apparent in flow patterns for four different times of day. The diurnal flow variations are particularly noticeable in the mesoscale divergence fields. The daily cycles are produced, presumably, by differential heating and frictional influences that are related to the topography. Mean vorticity patterns tend to extend vertically from the surface to 10 km, even though the flow direction changes markedly with altitude. Magnitudes of divergence and vorticity given by the objective analyses are within reasonable limits. For this particular tropical region, the correlation between vorticity and divergence in the earth's boundary layer is near zero, so there is apparently no marked tendency for convergence to be associated with cyclonic vortices.

IV A NUMERICAL FORECAST FOR SOUTH VIETNAM

In addition to making analyses of mean winds for September (discussed in Section III), we made analyses at particular synoptic times for July 1967, during the middle of the southwest monsoon. The average kinematic properties of these analyzed wind fields were very similar to those presented in Table I, and therefore appeared to be within reasonable bounds. The CRT displays of wind vectors showed changes in flow that reflect a combination of advection within the area of interest, diurnal and topographic effects, and synoptic-scale events encompassing a larger area than South Vietnam. The forecasting model described in Section II-D, like most existing models, is designed basically to handle advection and vorticity production, but not diurnal effects, which depend upon heating and topography. Also, the limited geographical extent of the region analyzed does not permit the model to anticipate effects that are part of relatively large weather systems (see Harris et al., 1969). In spite of these difficulties, we made some experimental numerical forecasts using real data for July.

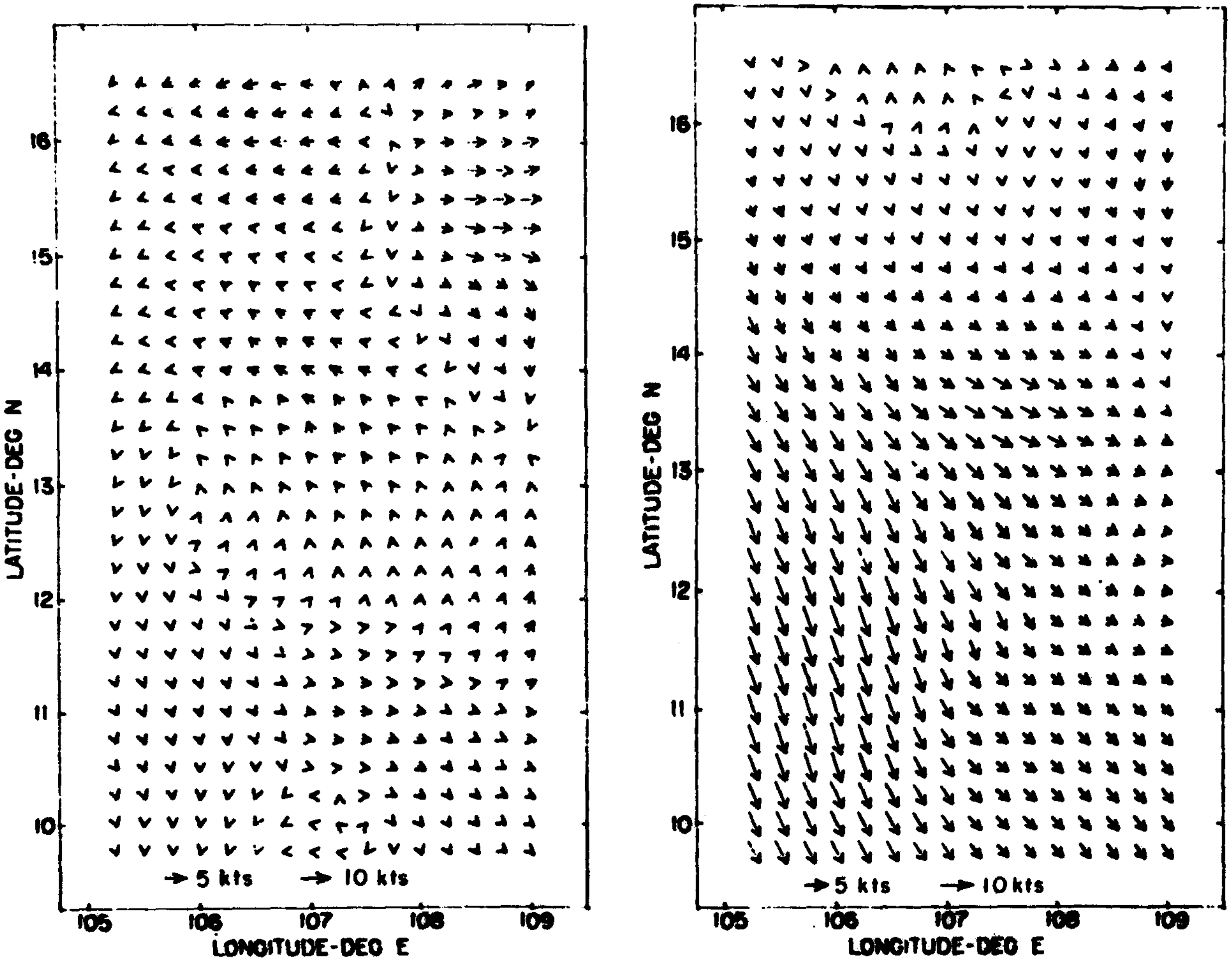
An analysis of the winds in the layer from the surface to 1 km at 0300 LST on 4 July 1967 is shown in Figure 7(a). The area analyzed has been increased in comparison with that shown earlier, in order to fill out a rectangular array. The isolines show the divergence field. Similarly, conditions in the 6 to 10-km layer are shown in Figure 7(b). (The intervening two layers are omitted for brevity.) Using the numerical model (Section II-D) with a one-hour time step, the vector wind changes that were forecast to occur during the next six hours are shown in Figure 8. The observed vector changes are shown for comparison. It can be seen that the predicted changes in Layer 1



(a) FOR THE SURFACE-TO-1-km LAYER

(b) FOR THE 6-TO-10-km LAYER

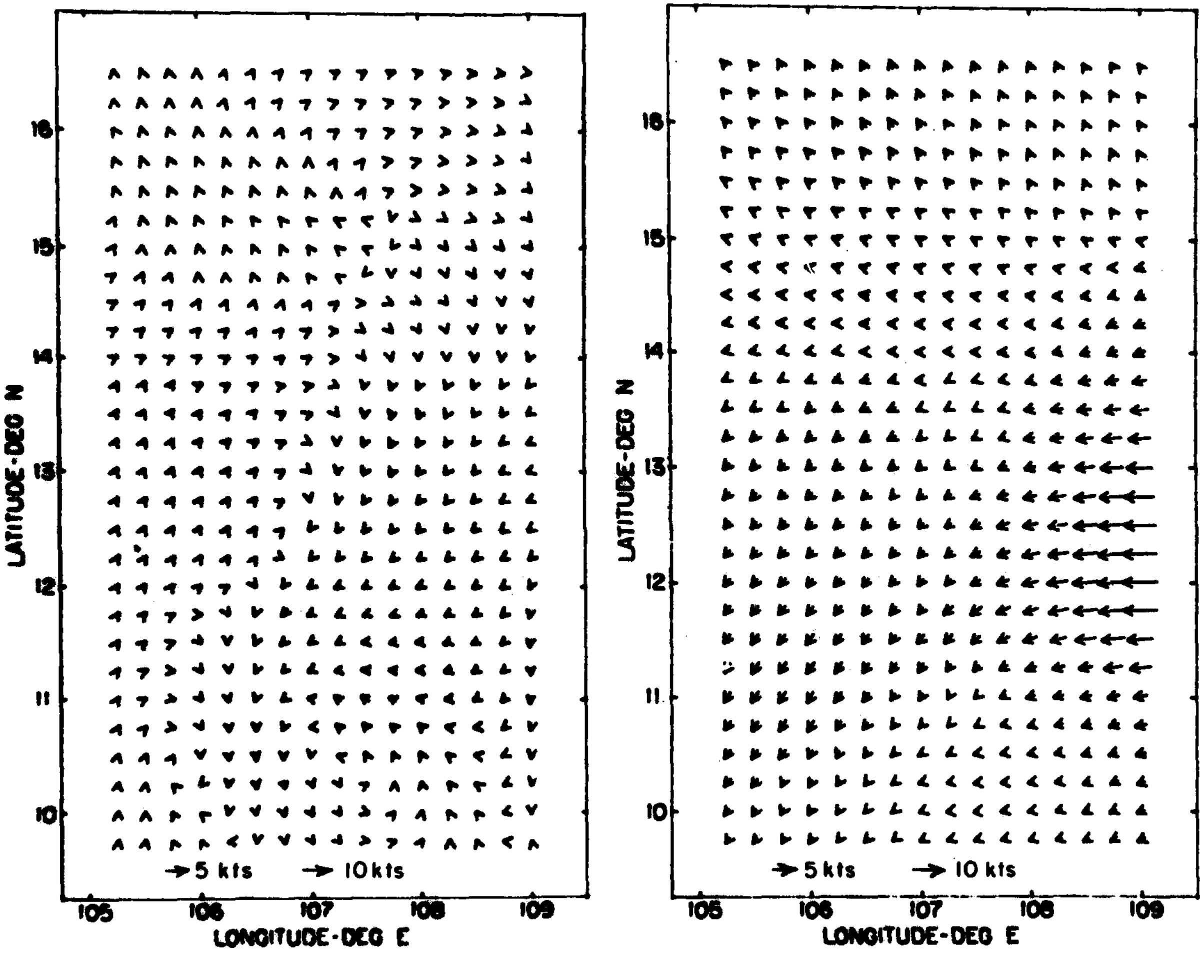
FIGURE 7 WIND VECTORS AND ISOLINES OF DIVERGENCE (in units of $10^{-6}\ s^{-1}$) AT 0300 LST ON 4 JULY 1967, USED AS INITIAL CONDITIONS IN A NUMERICAL FORECAST



(a) FORECAST CHANGES IN THE SURFACE-TO-1-km LAYER

(b) OBSERVED CHANGES IN THE SURFACE-TO-1-km LAYER

FIGURE 8 CHANGES IN WIND VECTORS IN SIX HOURS FOLLOWING 0300 LST ON 4 JULY 1967



(c) FORECAST CHANGES IN THE 6-TO-10-km LAYER

(d) OBSERVED CHANGES IN THE 6-TO-10-km LAYER

FIGURE 8 CHANGES IN WIND VECTORS IN SIX HOURS FOLLOWING 0300 LST ON 4 JULY 1967 are all quite small; however, the observed changes have a major consistent pattern over the southern half of the region. This change is of the synoptic-scale variety that cannot be handled in the model without encompassing a larger area. In Layer 4 the predicted vector changes are also quite small. The observed changes are also small except for an increase in the easterly current along the boundary near 12°N, 109°W. This case is rather typical of forecasts that have been made. The significance that we attribute to them is discussed in the next section.

V SUMMARY AND CONCLUSIONS

The experience gained in this study has led us to formulate the following viewpoints. In regard to objective analysis, we believe that the precedures of Section II are sufficiently accurate and versatile to be the equivalent of analogous subjective methods. Some major differences between tropical weather phenomena and those of midlatitudes are the weaker average circulations in the tropics, the smaller scales of most tropical disturbances, and the important effects of heating, topography, and release of latent heat. These apparent differences from extratropical conditions may of course be related to the smallness of the Coriolis parameter. The generally weaker circulations of the tropics are associated with relatively small (but still significant) vector changes in flow during periods on the order of one-half day. Such changes do not exceed observational errors by a very wide margin. For these reasons, we believe that tropical analyses must be more accurate and detailed than those of midlatitudes if useful numerical forecasts are to be made. In this context, the term "useful" may be defined as being significantly more accurate than "persistence." The requirements on tropical observations are therefore severe. However, the recent developments in data coverage provided by weather satellites, particularly the geosynchronous type, provide grounds for optimism in regard to making operational improvements in tropical forecasting. These new satellites show cloud patterns in a detail that permits measurements of cloud motions from a sequence of pictures (Fujita et al., 1969). At SRI, techniques for tracking cloud motions using a TV display (Evans and Serebreny, 1969) and also using computer techniques (Endlich, Wolf, Hall, and Brain, 1970) are being developed.

In addition to photographs in the visible spectrum, the next generation of NASA/ESSA synchronous satellites will obtain infrared data that will reveal cloud heights. Therefore, it will become possible to measure cloud motions at different altitudes for input to numerical models. In addition, further investigation may reveal that there are discernible relationships between cloud patterns and kinematic quantities such as divergence and vorticity. When such relationships become known, wind analyses that are based initially on standard data and cloud motions can be altered to conform to the kinematic patterns. One would expect that the initial conditions will become sufficiently accurate and detailed to permit tropical forecasting by numerical methods. It will become possible to test and evaluate improvements in the numerical techniques, and in the parameterizations of convection, boundary-layer drag, turbulence, etc. In summary, the writers believe that the best hope for making significant progress in tropical analysis and forecasting is to investigate the use of data from synchronous satellites, in combination with observations from rawinsondes and other sources, using procedures that are performed by computer to the maximum extent that is feasible.

Appendix

A METHOD OF LAGRANGIAN ADVECTION USING CONTINUOUSLY MOVING POINTS

Appendix

A METHOD OF LAGRANGIAN ADVECTION USING CONTINUOUSLY MOVING POINTS

In numerical prediction models, horizontal advection is often the predominating effect for typical weather patterns, and even if not predominating, is nearly always important. However, finite difference analogues for advection by the Eulerian method generally have the undesirable properties of smoothing out small-scale patterns and extrema in the original fields, and also of requiring short time steps for computational stability. The extent to which these limitations are present depends on the details of the Eulerian formulations used. The Eulerian method that we prefer is discussed in Section II-D. A Lagrangian advection method was also tested, as described in general terms below. The approach is somewhat similar to that of Krishnamurti (1962).

As is well known, in a pure Lagrangian method one keeps track of the positions of a set of particles. If horizontal advection of a scalar quantity Q is the only process occurring, a moving particle maintains its original value (Q_m) of the scalar quantity. Ideally, extrema in the Q field will be perserved by a Lagrangian technique. However, if one begins with a grid point analysis of Q, and uses an upwind scheme to locate a point that will arrive at the grid point after a specified time, according to our experience undesirable smoothing of the scalar field occurs. Therefore we have taken a different approach. The basic idea is that a moving set of points is tracked continuously, in addition to computing new grid-point values for each time step. The scalar values (Q_m) associated with these moving points are used in specifying the Q field at grid points at the end of each time step. The moving points could be taken, for example, as original observations (which maintain their values of Q), or in other ways that are described later. The new location of each moving point at the end of a time step is computed using the wind components at the nearest grid point. In the vicinity of the new location of each moving point, an objective analysis is made that assigns a weight (w_1) to each of the four nearest grid points. The weight is computed to be relatively large for close points, and also for an upwind-downwind orientation of the moving point and grid point, in comparison to a cross-wind orientation. This is in accord with the objective analysis method discussed in Section II-A. Also an intermediate quantity E_1 equal to w_1 times Q_m is computed at each of the four points. These steps are repeated for the next moving point. When a grid point treated previously is encountered again, values of E_1 and w_1 there are summed. After all moving points have been treated in this manner, the original grid-point values (Q_f) are also moved downstream (i.e., forward in time) to temporary new positions. The procedure then follows that described for moving points. At each of the four grid points nearest to the temporary location, a weight w_2 and a quantity E_2 equal to w_2 times Q_f are computed and summed with any previous values. All grid points are advanced in sequence. The final step is to combine the estimates found from the moving and fixed points by computing $E = E_1 + E_2$ and $w = w_1 + w_2$ at each grid point.

The new grid-point values at the end of the time step are $Q_f^* = E/w$, provided that $w > \epsilon$, where ϵ is a relatively small threshold value of the weight. Otherwise (mainly at inflow boundaries) the old value is maintained--i.e., $Q_f^* = Q_f$. The continuously moving points have their original values (Q_m), and new coordinates $x^* = x + u\Delta t$ and $y^* = y + v\Delta t$. Moving points that pass outside the region are dropped. The cycle is then repeated for the next time step.

In the use of the method so far, the moving points during a six- or twelve-hour forecast period were chosen for convenience as the grid-point values at the initial time (and not as observations, as mentioned previously for conceptual purposes). Therefore during the first time step, moving points and grid points are the same. Thereafter, the moving points pass through the wind field in an appropriate manner, carrying along their original values of the quantity of interest.

The method has been found to give comparatively good results in preserving small-scale features and extrema of the original field being advected. Time steps of one and two hours give almost identical results, with no evidence of instability, even in high-speed (midlatitude) flows. Further testing of this method is planned for a later time.

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13. ABSTRACT

Studies concerned with computer methods of analyzing and forecasting tropical weather patterns are summarized. The numerical techniques include a method of making grid-point analyses of winds, a method of balancing divergence fields in the vertical, a procedure for adjusting wind fields to "fit" cloud patterns, and a tropical forecasting model. Previously, these techniques were applied to synoptic scale analyses in the Caribbean. In this report, they are used to make mesoscale analyses of relatively dense data obtained by the Army in South Vietnam. For the month of September 1967, mean winds in four layers between the surface and 10 km were calculated for the hours 0300, 0900, 1500, and 2100 LST at each station. Objective analyses of these data on a one-quarter-degree latitude-longitude grid show the diurnal wind patterns associated with sea breezes and topographic effects. The variations in the mesoscale divergence fields in the boundary layer are particularly prominent. For this particular region, computed fields of divergence and vorticity in the boundary layer do not show any correlation, contrary to the experience of several other investigators for other tropical areas. Experimental short-range forecasts were made from the objective analyses, and appeared to be computationally satisfactory; however, the model was not able to include the diurnal effects. As a result of this work, we conclude that the most promising avenues for making significant progress in tropical forecasting depend upon use of new, high-density data (such as cloud motions and development shown by synchronous satellites), (over)

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ABSTRACT (continued)

computer methods of analyzing and synthesizing different kinds of information, and further refinement of numerical models that include convection and low-level effects related to heating and topography.