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Final Report

for

National Aeronautics and Space Administration

Grant NAG5-132

by

Stanley Q. Kidder

Department of Atmospheric Sciences
University of Illinois
Urbana, Illinois 61801

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NASA Technical Officer: Edward B. Rodgers

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1.0 INTRODUCTION

During the 1 1/2 years of grant sponsorship a Master's thesis was completed (Shyu, 1982) and a paper was presented at the 14th Technical Conference on Hurricanes and Tropical Meteorology (Kidder and Shyu, 1982). A paper for submission to the Journal of Applied Meteorology is in preparation and will be forwarded when complete. The scientific results obtained are outlined below.

2.0 SUMMARY OF SCIENTIFIC RESULTS

The basic idea of this project was to see if a relationship exists between satellite sounding data, which is plentiful in the tropics, and changes in tropical cyclone tracks or intensities. We eventually chose to expand the field of temperatures around the storm in terms of empirical orthogonal functions (EOFs) and to correlate the expansion coefficients of the most signficant few EOFs with five parameters: direction change, speed change, distance right of the persistence forecast location, distance ahead of the persistence forecast location, and intensity change. The data were mean layer temperatures for the layers 1000-500 mb, 500-250 mb, and 250-100 mb from the Scanning Microwave Spectrometer (SCAMS) on board the Nimbus 6 satellite. Fifteen typhoons and eleven tropical storms during the period July 1975 through April 1976 were studied.

The most important result is that the 250-100 mb mean layer temperatures apparently contains significant information about future locations of the storm. A 0.63 correlation coefficient was found between observed distance to the right of the persistence forecast location and a 24 h forecast of same made using EOF expansion coefficients. The correlation coefficient is increased to 0.67 by including data from all three levels in a single data vector. Twenty-four hour direction change is the next best forecast parameter (r = 0.56) followed by speed change (r = 0.53). Both of these use 250-100 mb temperatures. Distance ahead of persistence and intensity change show little signal. In general, the correlation coefficients decrease after 24 h.

It is interesting and somewhat surprising that upper-level temperatures contain the most information about tropical cyclone tracks. Winds at mid-levels, in contrast, are considered to be the best for steering the storm.

Much more detailed information can be found in Shyu (1982, Appendix A).

3.0 SUGGESTIONS FOR FUTURE WORK

Because the hurricane track forecasting problem is such an important one, it seems necessary to extend the above results. First, the more accurate data from the Microwave Sounding Unit (MSU) on board the current NOAA satellites should be applied to the problem. Second, it would be interesting to use brightness temperatures alone to make forecasts and to convert the retrieved temperatures to heights. The latter would facilitate comparison with forecasts made uisng steering-level winds. Third, experimentation with different grids could be useful. Finally, comparison with other data such as VAS soundings or with data from NOAA's program to observe the environments of hurricanes with dropwindsonde would be interesting.

4.0 REFERENCES

Kidder, S. Q., and K. Shyu, 1982: Tropical cyclone track forecasting using satellite sounder data. Paper presented at the 14th Technical Conference on Hurricanes and Tropical Meteorology, San Diego, June 7-11.

Shyu, K., 1982: A study of tropical cyclone motion using satellite sounder data. M.S. Thesis, University of Illinois, Urbana, 48 pp.

Appendix A

A STUDY OF TROPICAL CYCLONE MOTION USING SATELLITE SOUNDER DATA

BY

KAE SHYU

B.S., National Central University, 1972
M.S., National Central University, 1974

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Atmospheric Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1983

Urbana, Illinois

ABSTRACT

Although many dynamical and statistical prediction schemes are available to forecasters, tropical cyclone track errors are still large. One primary difficulty is that tropical cyclones exist over the data-sparse tropical oceans. Satellite sounders, however, routinely provide numerous data over these areas. Mean layer temperatures from the Scanning Microwave Spectrometer on board the Nimbus 6 satellite are decomposed using empirical orthogonal functions, and the expansion coefficients are related to deviations from the persistence forecast location, to speed change, to direction change and to intensity change. The significance of the regression equations is tested by a null hypothesis of zero correlation coefficient. It appears that significant information about tropical cyclone motion exists in the satellite-estimated mean layer temperatures, especially at upper levels. A physical interpretation of the statistical results is offered, and a one-storm-out independent test is used to test the stability of the equations. Finally, some further work is suggested.

ACKNOWLEDGMENTS

I wish to express my sincere thanks to my advisor Dr. Stanley Q. Kidder for his support, guidance and patience throughout this study.

This work was supported by the National Aeronautics and Space Administration under Grant No. NAG5-132. The Research Board of the University of Illinois provided some of the computer time.

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CHAPTER I

INTRODUCTION

Because of their extreme destructive capabilities, tropical cyclones have long been studied. Many dynamical forecast models (as reviewed by Elsberry, 1979) and statistical forecast methods (WMO, No.528, 1979) have been developed. But, despite these efforts, tropical cyclones are still not fully understood, and forecast errors are still large (Ramage, 1980; Neumann and Pelissier, 1981; Thompson et al., 1981). Incomplete representation of the physical processes in tropical cyclones and incomplete observations are possible reasons for the error (Elsberry and Frill, 1980).

Forecasting tropical cyclone tracks has been the prime concern for the operational meteorologist. Many operational methods have been developed. Analog models (Hope and Neumann, 1970; Jarrell et al., 1975) base a forecast on the average movement of past tropical cyclones having characterestics similar to the one being observed. Screening regression methods (Arakawa, 1964; Miller and Chase, 1966; Miller et al., 1968; Neumann and Hope, 1972; Neumann and Lawrence, 1975) select from a large number of possible predictors (such as climatology, persistence, sea level pressure, standard pressure level height, height change, thickness, thickness change, wind, past movement of tropical cyclone center, numerically forecast data and even time of the year) a small set of predictors and then develop prediction equations. Some numerical models (Harrison, 1973; Sanders et al., 1975; Hovermale and Livezey, 1977) have been also devised. Different methods give different forecasts of tropical cyclone tracks. Basic improvements need to be made in order to produce better forecasts (Elsberry and Frill, 1980; Neumann, 1980; Ramage, 1980). None of these attempts directly use satellite sounding data. Miller and Chase (1966) pointed out sixteen years ago, that the prediction of tropical cyclone motion should be based on the field of motion over a large area sourrounding the vortex and that a more desireable dynamic approach might have to wait for vastly improved data networks in the tropical regions.

Although most tropical cyclones develop in, and track across, data sparse regions, weather satellites provide the means whereby the most remote tropical cyclones can be tracked. Fett and Brand (1975) tried to use consecutive daily satellite cloud patterns to forecast 24 hour movement of tropical cyclones. This method is quite subjective, however. When evaluated in Guam it failed to contributed to forecasting skill (Ramage, 1980). Up to now, no quantitative attempt has been made to use satellite sounding data to forecast tropical cyclone tracks.

Recently Chan et al. (1980), based on composited rawinsonde data, found that the sign of the vertical shear between 200 mb and 900 mb of the environmental wind in the direction of the tropical cyclone motion was related to the tropical cyclone turns. They suggest that tropical cyclone motion can be related to the mean tropospheric temperature field of the environment. Gray (1980) also pointed out that in future hurricane research we should not neglect the hurricane's outer 5-10 degree radius structure which is primarily responsible for the hurricane's current and future motion.

It is the purpose of this paper, therefore, to study the statistical relation between tropical cyclone motion (turning motion and accelerating motion) and environmental temperatures determined from satellite sounder data. Nimbus 6 Scanning Microwave Spectrometer (SCAMS) data will be used because of its ability to probe cloud-shielded weather systems and provide temperature soundings under nearly all weather conditions.

CHAPTER II

OBSERVATIONAL DATA

This study concentrated on the Western North Pacific region (110E-160E, 0N-30N) for the period July 1975 through April 1976. Fifteen typhoons and eleven tropical storms were included in the sample. Track data were from the 1975 and 1976 Annual Typhoon Reports prepared by the Joint Typhoon Warning Center. Track data at 00, 06, 12, and 18 GMT were interpolated to obtain positions at 03 and 15 GMT, the times of satellite observation of the region. Five parameters relating to tropical cyclone motion were defined. Two (X and Y) describe persistence forecast position errors in the directions perpendicular to and parallel to the persistence forecast direction of the storm (Fig. 2.1). Another two (S and D) are the speed change and direction change of the velocity of the tropical cyclone during the forecast period. The last one (I) is the intensity change.

The Nimbus 6 spacecraft, launched 12 June 1975, was placed in a sun-synchronous polar orbit at an altitude of approximately 1100 km. The satellite had local noon (ascending) and midnight (decending) equator crossings and an 81 degree retrograde inclination. Successive orbits crossed the equator with 26.8 degrees of longitude seperation, and the orbital period was about 107.25 minutes (Staelin et al., 1975).

The scanning microwave spectrometer on board Nimbus 6 is a five-channel radiometer. The radiance observed was used to retrieve the tropospheric temperature profiles and the water vapor and the liquid water content in the atmosphere. The frequencies of the five channels nominally are 22.235, 31.65, 52.85, 53.85 and 55.45 GHz. The latter three frequencies are within the 5 mm

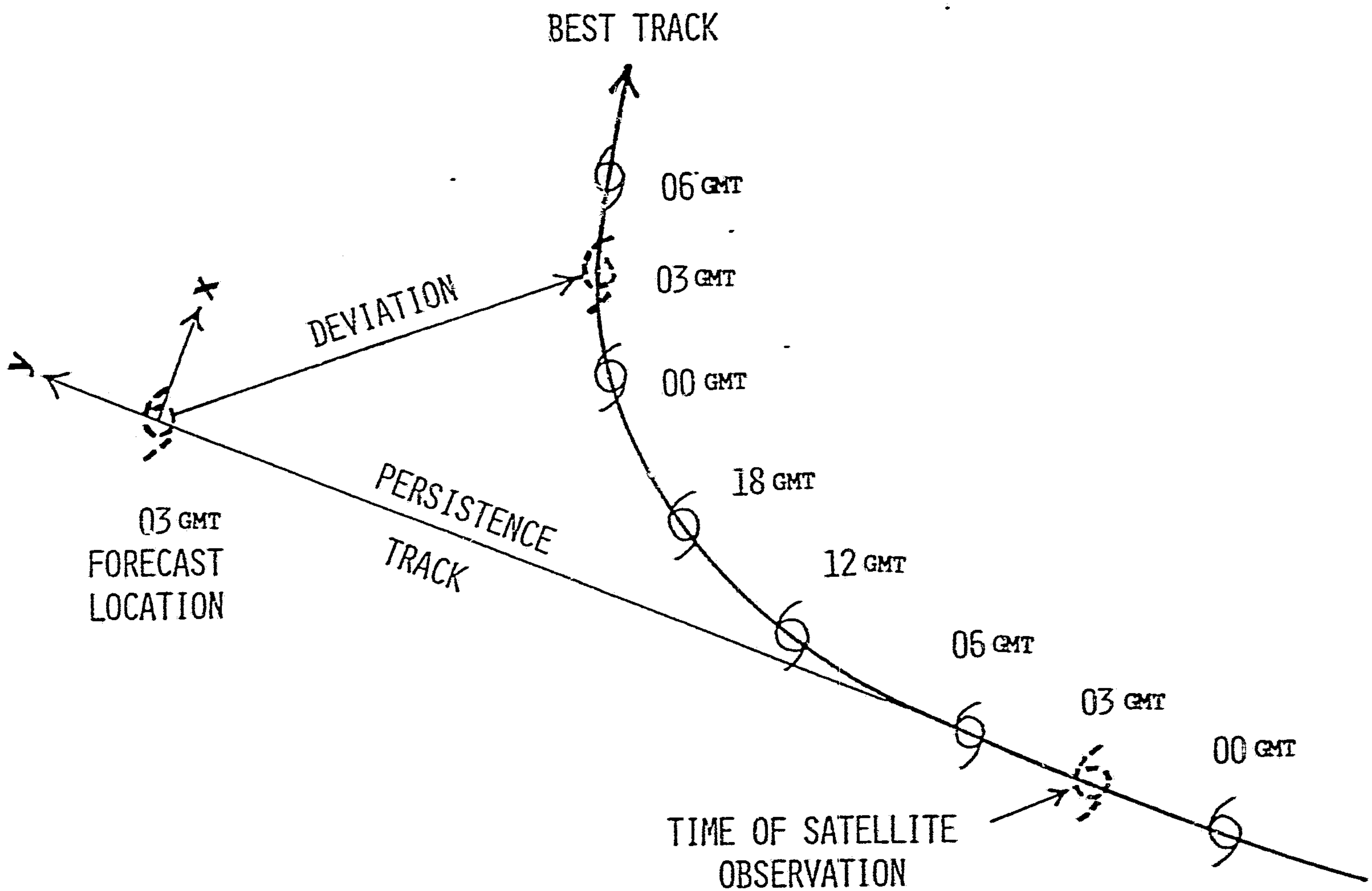

Fig. 2.1. Parameters defining the persistence forecast position error.

oxygen absorption band and are used for sounding the atmosphere. The frequency of channel 1 is located near a water vapor line and channel 2 is in an atmospheric window. These two channels are used to measure vertically integrated atmospheric water vapor and liquid water content. The SCAMS instrument scans across the spracecraft track in 7.2 degree increments. For every 16 seconds there are thirteen data samples between 43.2 degrees to the left of nadir and 43.2 degrees to the right of nadir. The antenna beamwidth of 7.5 degrees results in a spatial resolution of approximately 145 km at nadir degrading to 220 km downtrack by 360 km crosstrack at the maximum scan angle. The -43.2 to +43.2 degrees of earth scan cover a 2400 km swath on the earth (Staelin et al., 1975). The orbit and scan geometries are such that the earth is sensed twice per day. The data are recorded on magnetic tapes and archived at the National Space Science Data Center.

The ability of the SCAMS data to retrieve temperatures accurate to within the design limits of the instrument was assured by the study of Grody and Pellegrino (1977). Mean layer temperatures retrieved from SCAMS data are more accurate than those for a discrete level (Waters et al., 1975); so the satellite data used in this study are the mean temperatures from the layers 1000-500 mb, 500-250 mb, and 250-100 mb from the Scanning Microwave Spectrometer on board the Nimbus 6 satellite. According to Staelin et al. (1975b), microwave spectrometers can measure temperature differenecs of deep layers accurate to within a few tenths Kelvin. Only temperature differences, not absolute temperatures, were used in this study.

In order to ensure a homogeneous data set for the analyses, storms with intensity less than 34 knots or centers north of 30°N or which made unusual loop turns were eliminated from the sample. It was felt that seperate forecast techniques would be necessary for these cases. Tropical storms having no satellite observations or too few for objective analysis were also eliminated. To minimize contamination by precipitation, soundings with liquid water contents greater than 0.5 kg/m^2 (as estimated by the SCAMS data) were not used in the objective analysis. According to Staelin et al. (1975b) this will eliminate most of the contaminated data. In the end there were 67, 58, 50 and 40 observations, respectively, for 12, 24, 36 and 48 hour forecasts.

The stereographical horizontal map projection having the tropical cyclone as the pole (Shenk et al., 1971) was adopted to track the translating tropical cyclone. As discussed in detail by them, the map distortions are independent of the latitude of the center. A square domain, centered over the tropical cyclone center, extending 18° latitude on each side of the storm was used to analyze the temperature field from satellite soundings. The square domain was oriented in the direction of storm motion. The grid size of the square domain was 4° latitude (Fig. 2.2). Approximately 1000 individual soundings can be obtained in an 18° circle for every 12 hour period. Objective analysis (Cressman, 1959; Inman, 1970) was applied to these rather irregularly distributed data points to interpolate the temperature data to 100 grid points of the square domain. Three scans were performed in the objective analysis to make successive corrections. After objective analysis only the inner 64 grid points are used for further study. In addition, an 8° latitude resolution grid was constructed by averaging data on the 4° grid for later use. Sixty-seven original temperature fields were obtained.

The temperature fields were normalized by subtracting the mean of the four grid points surrounding the storm center from the original temperature field. The mean normalized temperature field for each layer was calculated

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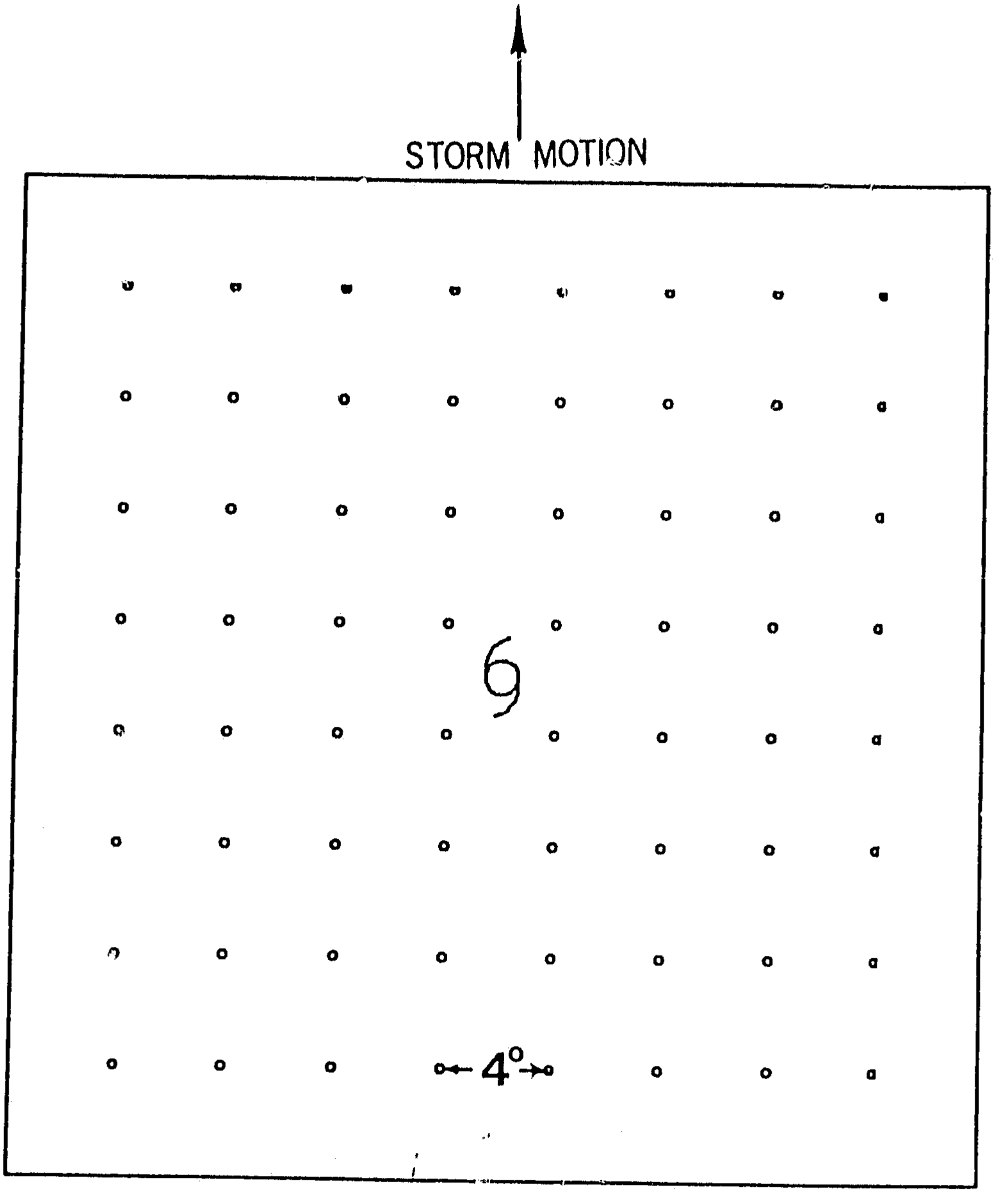

Fig. 2.2. Data grid for empirical orthogonal function analysis of SCAMS data.

and the temperature deviations from these mean fields were computed. The temperature deviation fields are used in the empirical orthogonal function analysis.

CHAPTER III

EMPIRICAL ORTHOGONAL FUNCTION ANALYSIS

Empirical orthogonal functions have the advantage that they provide the most economical representation of a large set of observations and still account for most of the variance of the data fields. Many meteorological studies using empirical orthogonal functions have been done and have shown great usefulness (Kutzbach, 1967; Stidd, 1967; Davis, 1976; Smith and Woolf, 1976; Murakami, 1980; Hunter et al., 1981; Walsh and Richman, 1981). Empirical orthogonal functions are derived and applied as follows. Let T be the matrix of temperature deviations

$$T = \begin{bmatrix} T_{11} & \cdots & T_{1N} \\ & \cdots & \\ T_{M1} & \cdots & T_{MN} \end{bmatrix}. \qquad (3.1)$$

where M is the number of the observations and N is the number of grid points in the domain. The covariance martix of the temperature deviation fields is

$$\tilde{T} = \frac{1}{M} T^T T. \qquad (3.2)$$

The eigenvectors of $\tilde{T}$ are the empirical orthogonal functions. Let T^* be the matrix whose columns are the eigenvectors of $\tilde{T}$. Because the eigenvectors form an orthonormal basis for an N-dimensional vector space, we can expand the temperature deviation fields as

$$T = AT^{*T}. \qquad (3.3)$$

Matrix A is the matrix of expansion coefficients. It can be shown that $A^T A$ is a diagonal matrix (unlike $T^T T$) which means there are no correlations between different expansion coefficients. This orthogonal property of the expansion coefficients provides independent predictors so that we can add or substract one predictor to or from the prediction scheme without recalculation of the other computed coefficients.

In order to study the relation between the temperature deviation fields and tropical cyclone motion, five parameters relating to tropical cyclones were used as predictands. The least squares criterion was applied to find the regression coefficients of these predictands in terms of predictors. Let B be the predictand matrix. We want to find the matrix C such that

$$B = CA^T. \tag{3.4}$$

The least squares solution is simply

$$C = BA(A^TA)^{-1}. \tag{3.5}$$

It should be noted that we can bypass the use of the intermediary expansion coefficients A. From orthogonal properties

$$A = TT^*. \tag{3.6}$$

then

$$B = CT^{*T}T^T. \tag{3.7}$$

or

$$B = DT^T. \tag{3.8}$$

where

$$D = CT^{*T}. \tag{3.9}$$

If we use all eigenvectors to calculate D then this is the same as the ordinary regression solution.

$$D = (BT)(T^TT)^{-1}. \tag{3.10}$$

However, the eigenvectors can be ordered by the magnitude of their corresponding eigenvalues, and the first few eigenvectors will usually explain most of the variance of the data field. The rest can be discarded. In practice, to calculate C or D, one simply uses a modified $T^*(T^*_M)$ which has only as many columns as there are significant eigenvectors. This eigenvector expansion method has the advantage that it is less affected by the measurement errors than the ordinary regression solution (Smith and Woolf, 1976).

How many eigenvectors are sufficient for analysis is an important problem. If too few eigenvectors are used, some important information will be lost. If too many eigenvectors are used, the problem of artifical predictability should be considered (Davis, 1976). A Monte Carlo test suggested by Preisendorfer and Barnett (1977) was applied to find significant eigenvalues with 95% confidence. Those eigenvectors corresponding to significant eigenvalues were retained in the analysis.

CHAPTER IV

RESULTS

A. Basic Fields

The mean normalized temperature fields are shown in Fig. 4.1. The 1000-250 mb field is simply an average of the 1000-500 mb and 500-250 mb fields. It is included for comparison with Chan *et al*. (1980). Warmer temperatures in the tropical cyclone center are observed except in the 250-100 mb layer where (near the tropopause) the temperature is colder toward the equator. The temperature deviations from these mean fields were used for empirical orthogonal function analysis.

After empirical orthogonal function analysis of the satellite-estimated temperature fields, the number of significant eigenvectors (Table 4.1) was determined by the Monte Carlo technique (see above). The variance explained by these significant eigenvectors for each case is shown in Table 4.2. The column labeled "3-layer" is for a predictor field formed by averaging the data in the 1000-500 mb, 500-250 mb, and 250-100 mb grids to form 8° resolution data, and then including data from all three layers in a single data vector. The result is a predictor which sacrifices horizontal resolution (8° versus 4°) to get information at all vertical levels. Fewer than six eigenvectors are necessary to explain more than 90% of the variance in the satellite-estimated temperature fields; empirical orthogonal functions indeed provide an economical representation and still explain most of the variance in the data set.

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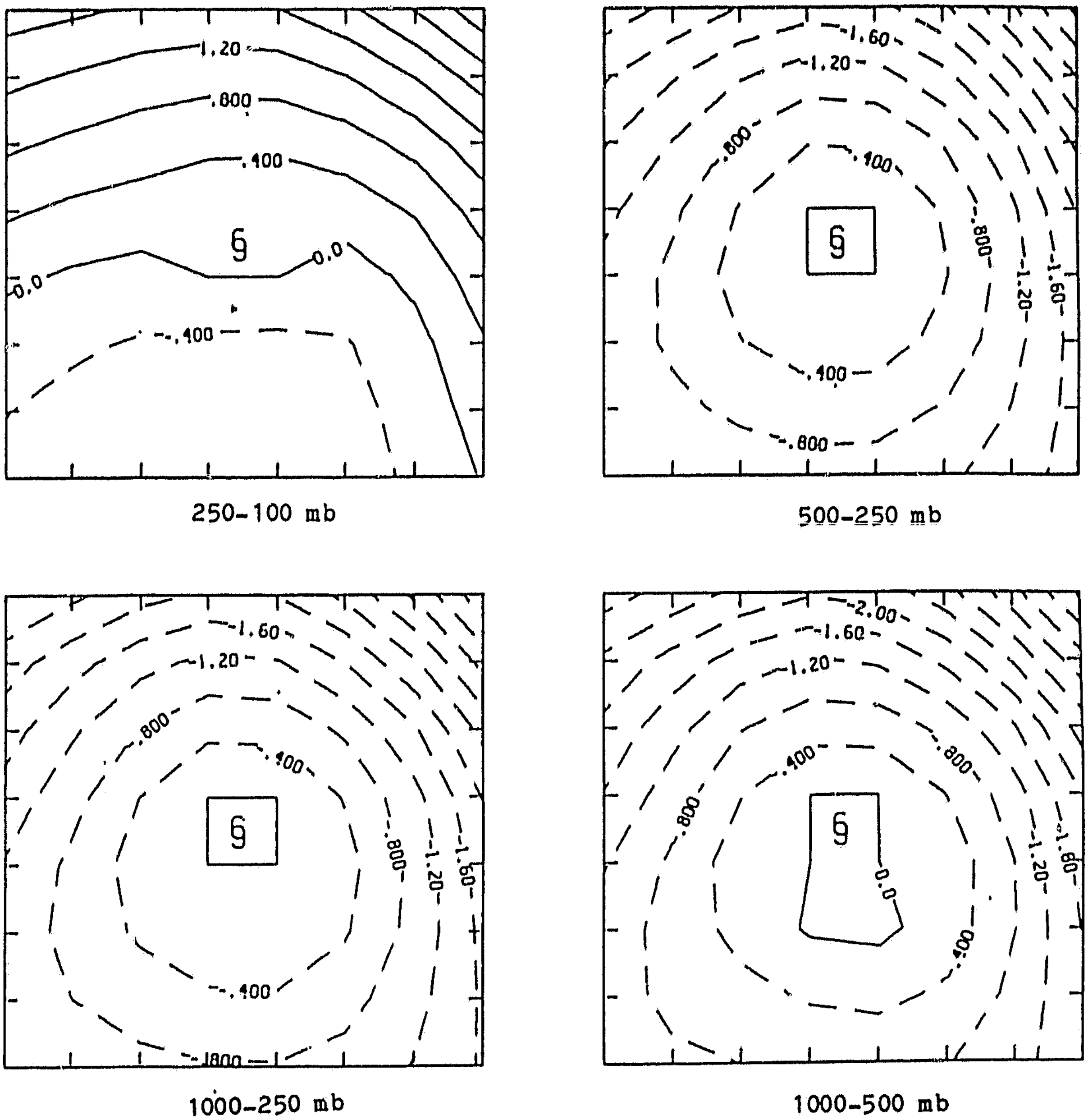


Fig. 4.1. Mean of the normalized layer mean temperature fields (K).

Table 4.1 Number of significant eigenvectors for each layer

1000-500mb	500-250mb	250-100mb	1000-250mb	3-layer
5	5	5	5	6

Table 4.2 Variance explained by the significant eigenvector set

1000-500mb	500-250mb	250-100mb	1000-250mb	3-layer
92.1%	94.3%	94.1%	93.4%	91.5%

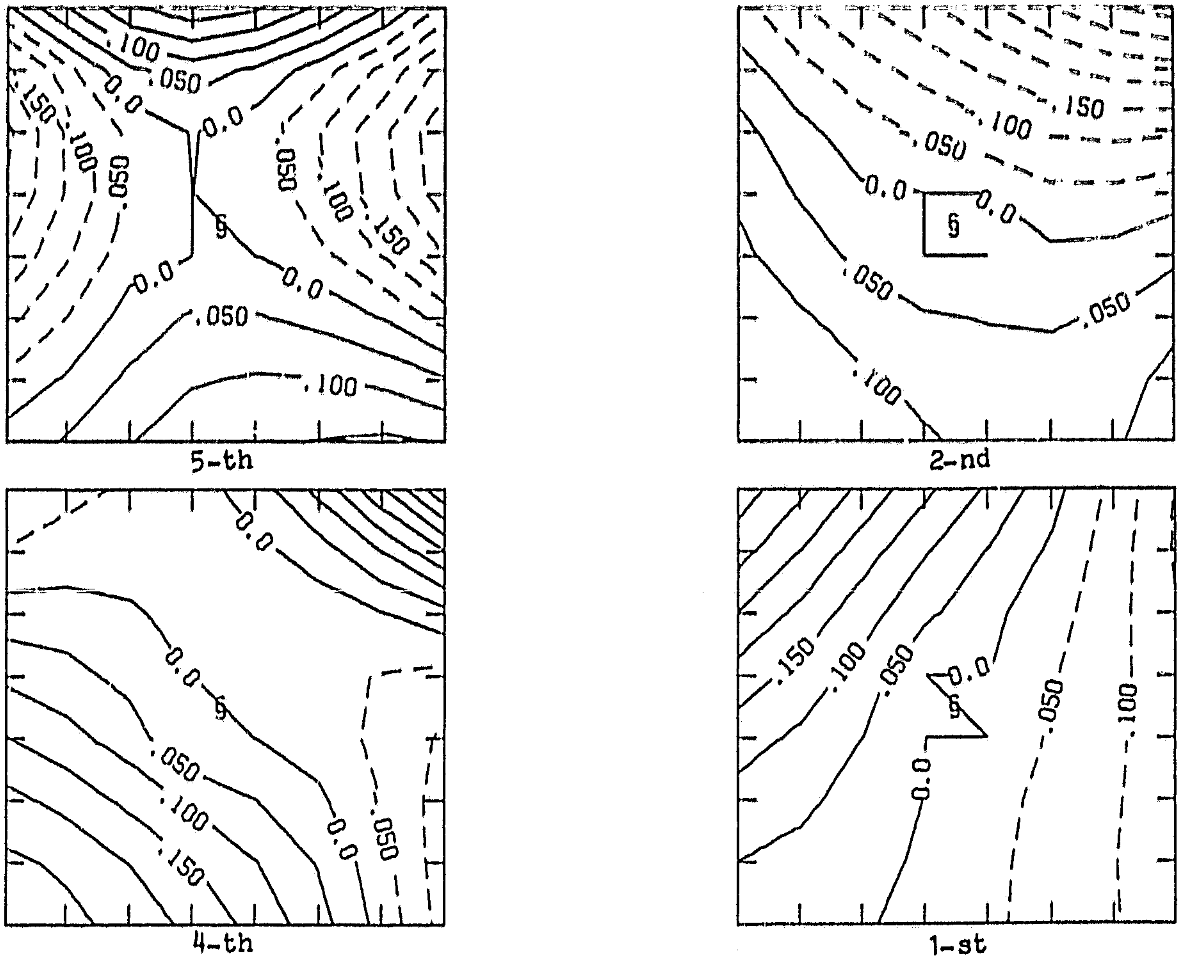
Plots of eigenvectors for every predictor layer are shown in Fig. 4.2 to 4.6. For the 250-100 mb layer and the three layer combination, the variance explained by individual significant eigenvectors is shown in Table 4.3 and Table 4.4.

B. Statistical results

The number of significant eigenvectors listed in Table 4.1 was used as an orthogonal function set to expand the temperature deviation fields, and the analysis described in Chapter III was performed. The correlation coefficients between the predicted and observed values for the five parameters relating to the storm motion, as defined in Chapter II, are shown in Tables 4.5 to 4.8.

A null hypothesis of zero correlation was tested with 5% level of significance to determine the statistical significance of the correlation coefficients. The number of degrees of freedom was intentionally halved to account for the fact that we have several observations of some storms; thus the observations are not completely independent. Table 4.9 shows the number of degrees of freedom and the critical values of the correlation coefficients. The ′ in Tables 4.5 to 4.8 indicates significance.

For 12 hour forecasts, except for direction change and intensity change, every correlation coefficient is greater than the critical value and thus appears to be significant. This suggests that the mean layer temperature of each predictor layer contains information about the displacement of the tropical cyclone right of persistence, and ahead of persistence and about the speed change of the tropical cyclone. For direction change, only mean temperatures in the 250-100 mb layer and the three layer combination contain significant information. For intensity change the correlation coefficients for every layer are around the significance or noise level. Little significant



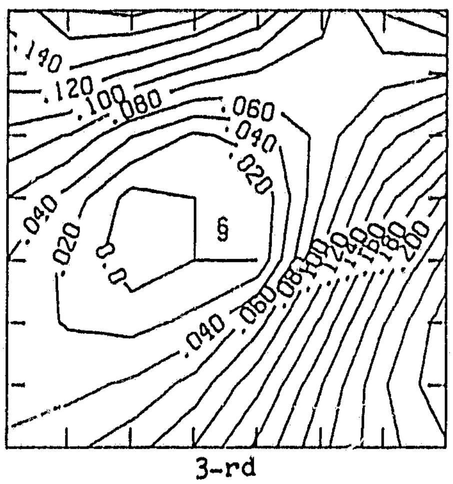
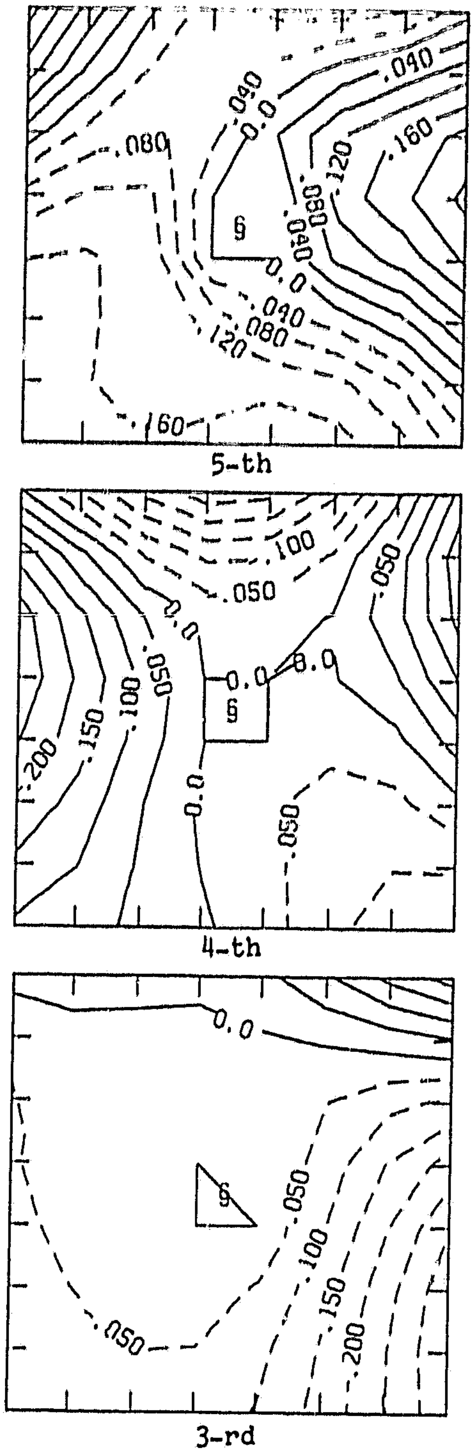


Fig. 4.2. First five eigenvectors for 250-100 mb temperature deviation fields.



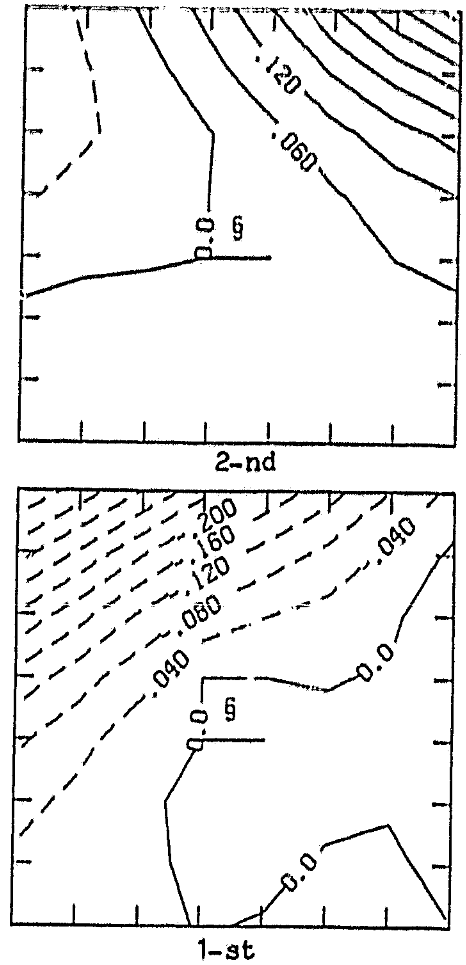
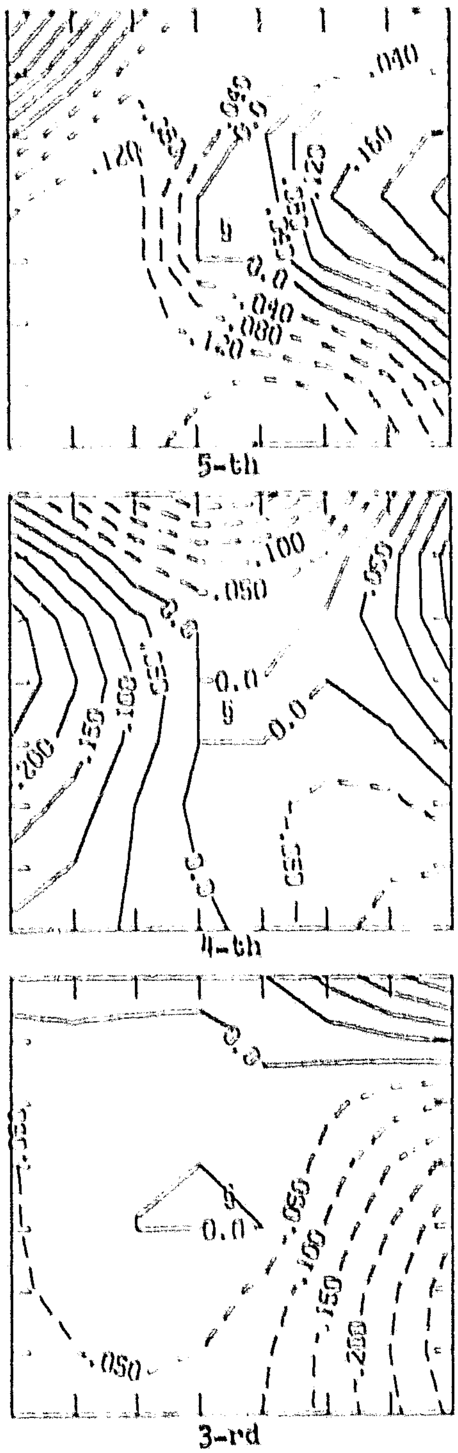


Fig. 4.3. First five eigenvectors for 500-250 mb temperature deviation fields.



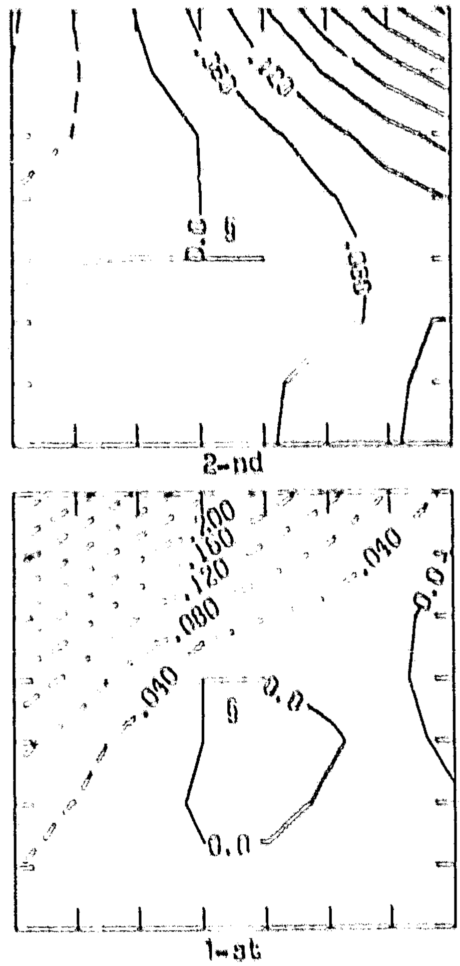


Fig. 4.4. First five eigenvectors for 1000-500 mb temperature deviation fields.

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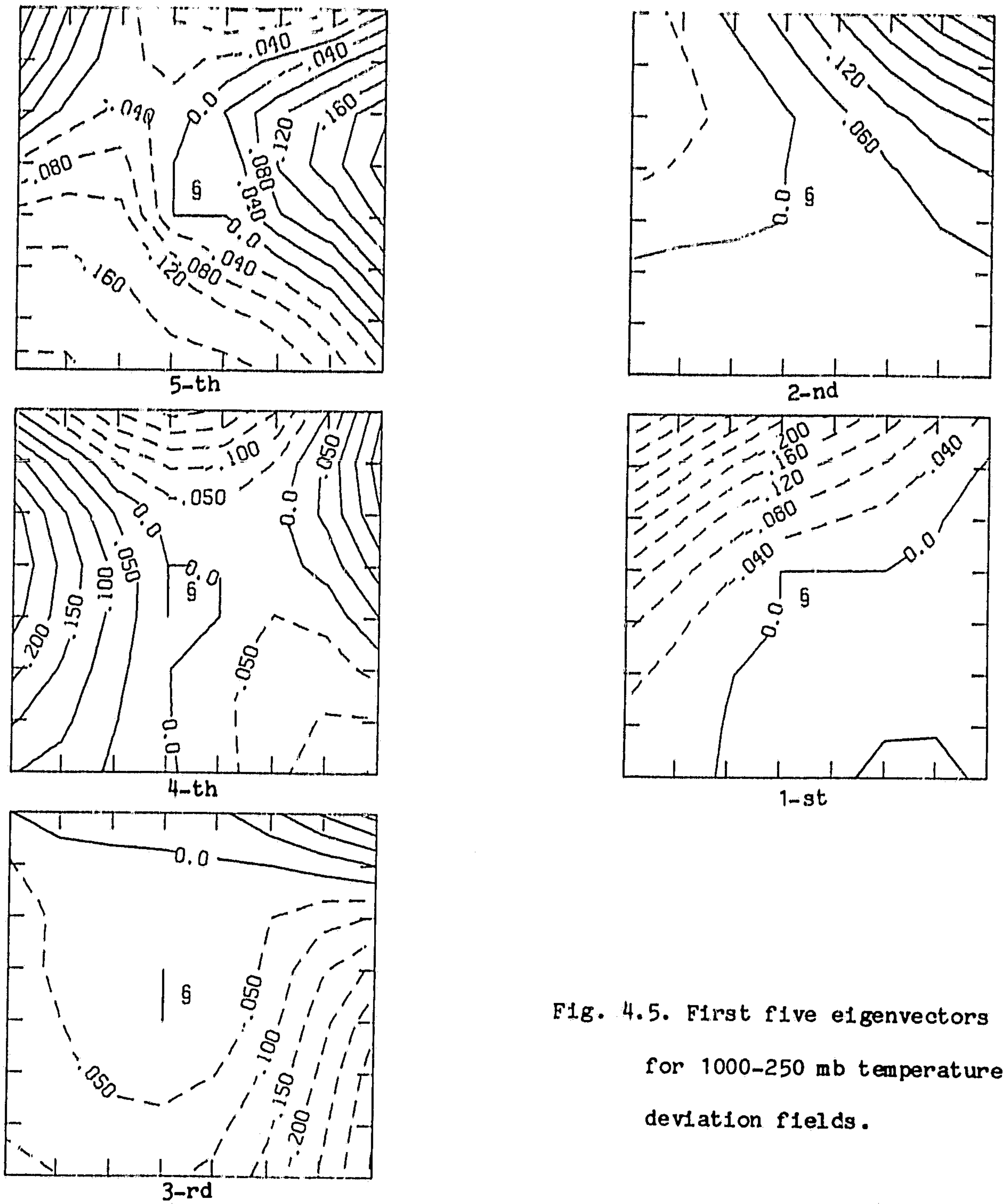

Fig. 4.5. First five eigenvectors for 1000-250 mb temperature deviation fields.

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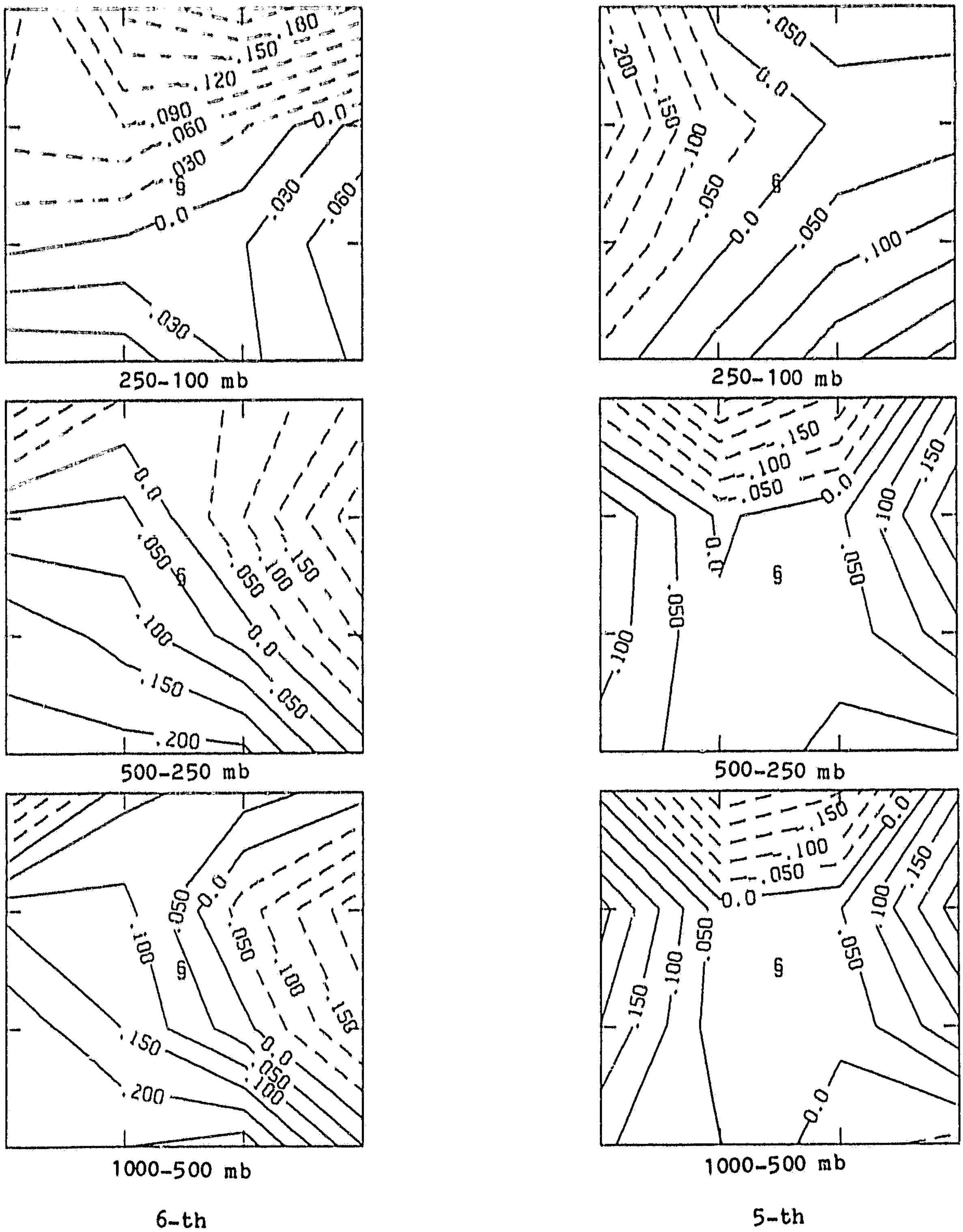


Fig. 4.6. First six eigenvectors for the three layer combination temperature deviation fields.

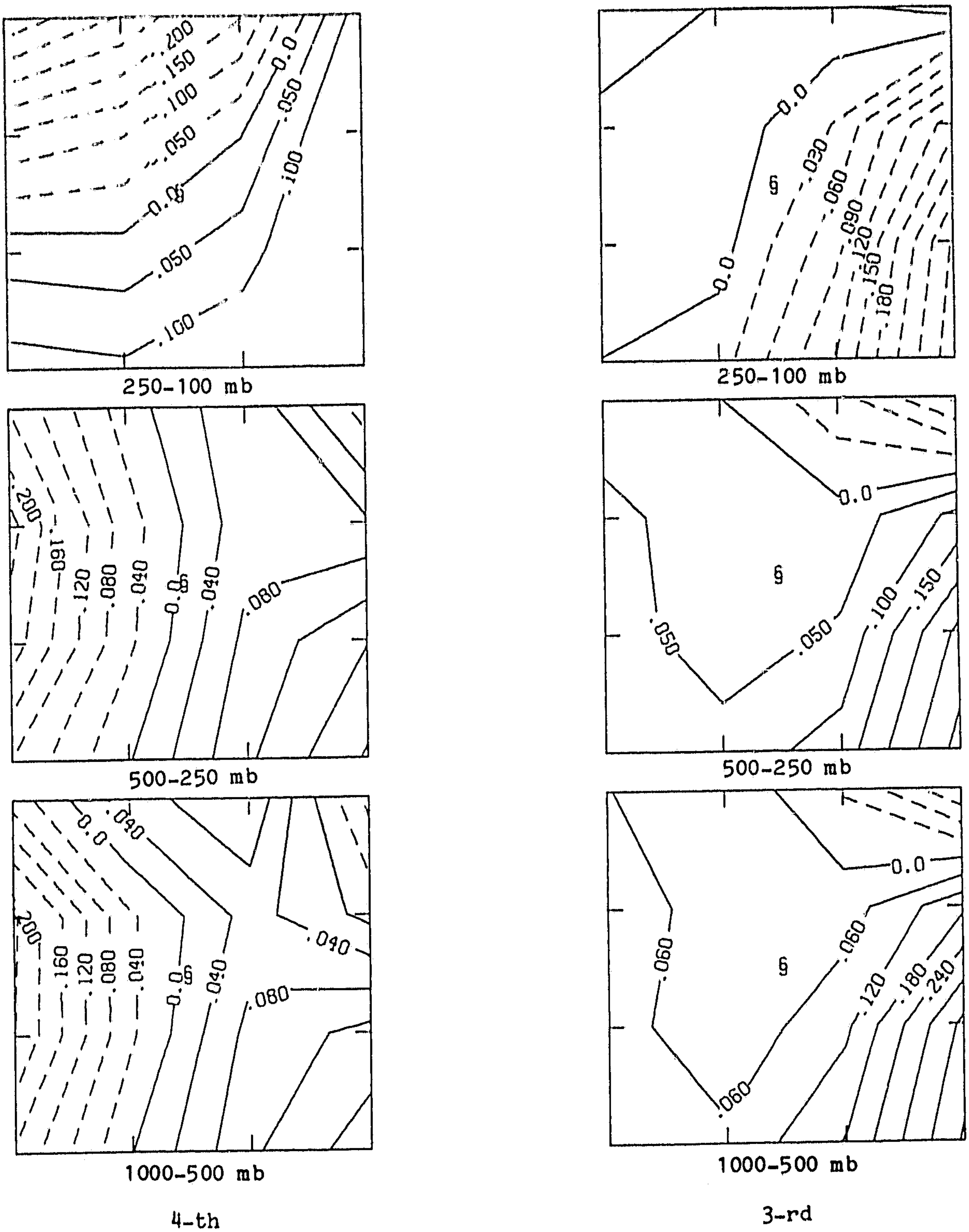


Fig. 4.6. Continued.

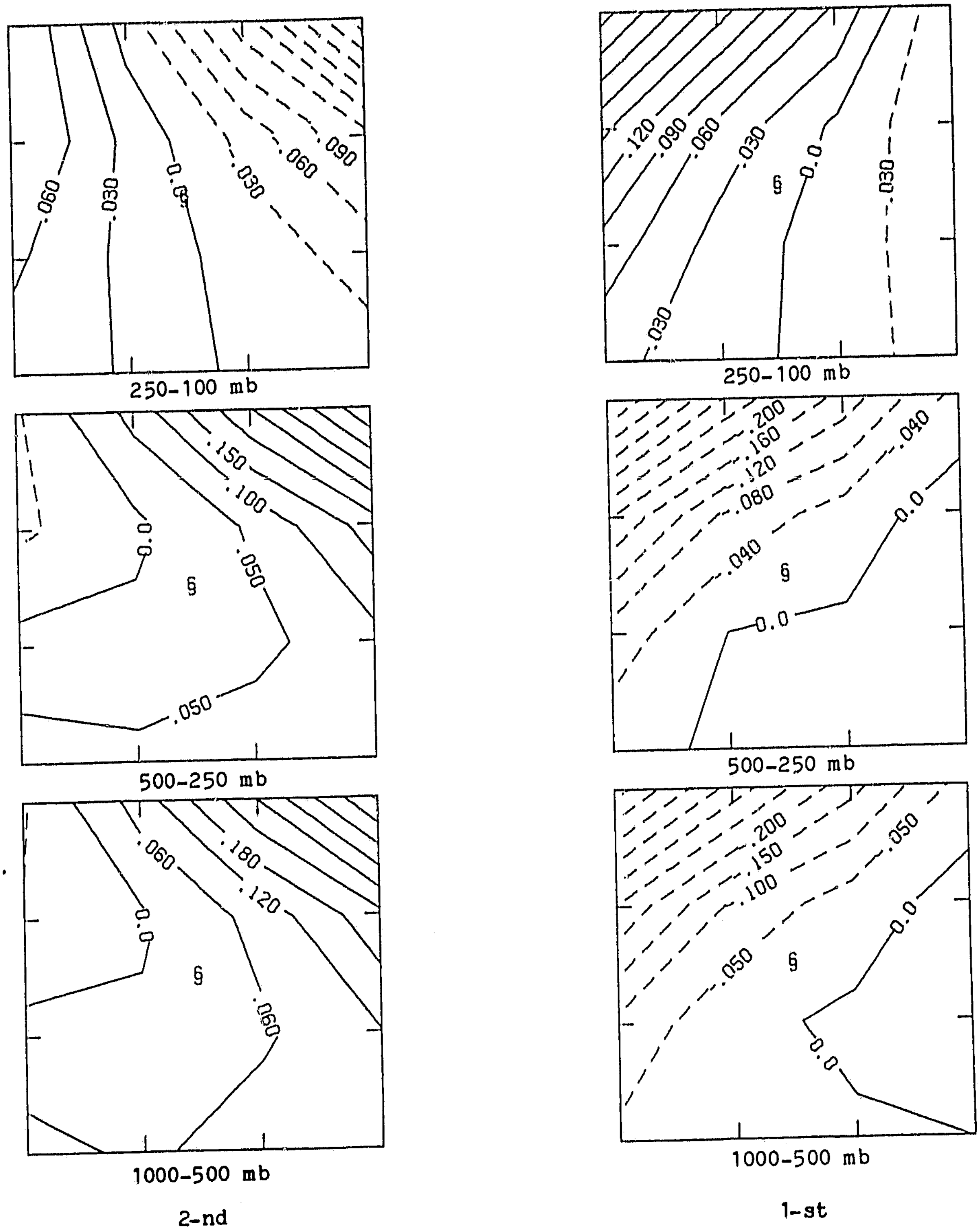


Fig. 4.6. Continued.

Table 4.3 Variance explained by first five eigenvectors individually for the 250-100 mb layer

1-st	2-nd	3-rd	4-th	5-th
55.2%	17.7%	12.8%	5.0%	3.4%

Table 4.4 Variance explained by first six eigenvectors individually for the three layer combination

1-st	2-nd	3-rd	4-th	5-th	6-th
49.5%	18.7%	11.2%	4.9%	4.2%	3.0%

Table 4.5 Correlation coefficients between predicted and observed values for 12 hour forecasts

	1000-500mb	500-250mb	250-100mb	1000-250mb	3-layer
X	0.47′	0.46′	0.54′	0.47′	0.58′
Y	0.47′	0.44′	0.44′	0.46′	0.53′
D	0.34′	0.30	0.49′	0.33	0.49′
S	0.42′	0.40′	0.39′	0.41′	0.45′
I	0.35′	0.34′	0.32	0.33	0.35′

X, Y = persistence forecast error (Fig. 2.1).

D = direction change. S = speed change.

I = intensity change.

Table 4.6 Same as Table 4.5 except for 24 hour forecasts

	1000-500mb	500-250mb	250-100mb	1000-250mb	3-layer
X	0.42′	0.40′	0.63′	0.40′	0.67′
Y	0.32	0.30	0.38′	0.31	0.39′
D	0.32	0.28	0.56′	0.29	0.61′
S	0.49′	0.47′	0.53′	0.48′	0.51′
I	0.25	0.38	0.29	0.31	0.29

Table 4.7 Same as Table 4.5 except for 36 hour forecasts

	1000-500mb	500-250mb	250-100mb	1000-250mb	3-layer
X	0.43′	0.36	0.62′	0.43′	0.64′
Y	0.31	0.26	0.37	0.31	0.39′
D	0.27	0.28	0.44′	0.27	0.49′
S	0.49′	0.46′	0.51′	0.49′	0.50′
I	0.36	0.41′	0.33	0.36	0.37

Table 4.8 Same as Table 4.5 except for 48 hour forecasts

	1000-500mb	500-250mb	250-100mb	1000-250mb	3-layer
X	0.40	0.32	0.54′	0.35	0.50′
Y	0.33	0.31	0.29	0.32	0.30
D	0.37	0.35	0.49′	0.35	0.48′
S	0.22	0.22	0.37	0.22	0.17
I	0.32	0.40	0.39	0.34	0.34

Table 4.9 Degrees of freedom (DOF) and the critical values (CRI) of the correlation coefficients

	12 hour	24 hour	36 hour	48 hour
DOF	32	28	24	19
CRI	0.337	0.361	0.388	0.433

information about 12 hour intensity change is contained in the satellite-estimated mean layer temperatures.

For 24 hour forecasts, only displacement right of persistence and speed change contain significant information from all of the five predictor layers, but the 250-100 mb layer and the three layer combination are relatively better. For the displacement ahead of persistence and direction change only the 250-100 mb layer and the three layer combination are above the significance level. Only the 500-250 mb layer seems to contain any significant information about intensity change.

For 36 hour forecasts, only speed change seems to have significant information in all five predictors, and each layer is almost equally good. The highest correlation coefficients are for displacement right of persistence using the 250-100 mb layer and the three layer combination as predictors. None of the five predictors contain significant information about displacement ahead of persistence. Direction change only has significant information in the 250-100 mb layer and in the three layer combination. The 500-250 mb layer is the only layer which contains significant information about the 36 hour intensity change.

For 48 hour forecasts, the displacement right of persistence and direction change only have significant information in the 250-100 mb layer and the three layer combination. None of the five predictors contain significant information about 48 hour displacement ahead of persistence, speed change, or intensity change.

It is interesting to note that in general the best single layer for forecasting storm motion is the 250-100 mb layer; that is upper-level temperatures make the best predictors. This is in constrast to motion forecasts made using environmental winds; mid-level winds are the best predictors (e.g. George and Gray, 1976). It is also interesting to note that the three layer combination is generally a slightly better predictor than the 250-100 mb layer. First, this indicates that upper-level information dominates the lower levels. Second, because the three layer combination had only an 8° grid spacing versus 4° for the single layers, it would be interesting to repeat the experiment using a coarser grid which would then cover a larger geographical area. Since longer-range forecasts require information further from the storm, a larger grid might improve the 36 and 48 hour forecasts.

Based on a small sample of data, Chan et al. (1980) suggested that tropical cyclones tend turn if they encounter a gradient of 1000-250 mb mean layer temperatures in front of them. The results presented here indicate that their suggestion is probably not statistically significant.

In summary, it was found that

1. The correlation coefficients decrease with time after 24 hours.
2. Upper-level temperatures seem to contain more information on storm motion than middle or lower levels.
3. X and direction change are the best predicted quantities followed by Y and speed change.
4. Intensity change is not well forecast with mean layer temperatures.

Because there are relatively few observations in the sample, no data points could be reserved for an independent test. Instead a one-storm-out independent test procedure (Hunter et al., 1981) was used to test the performance of the prediction equations. If one removes all observations of a single storm from the sample, the first few eigenvectors change very little. Alternately, one can view the eigenvectors derived from all of the observations as a set of orthonormal basis vectors with which any vector field can be expanded. The one-storm-out procedure uses eigenvectors derived from all of the storms and tests the sensitivity of the regression coefficients (C matrix). Each time all data points belonging to a given storm were deleted from the data sample. The other data points were used to redevelop the prediction equations (i.e. to calculate the regression coefficients). Then the newly developed prediction equations were used to make forecasts for the deleted storm. This testing procedure is repeated, cyclically, until all the storms are used as independent data. The correlation coefficients between the values predicted by the one-storm-out procedure and the observed values were calculated as for Tables 4.5 to 4.8. Table 4.10 shows the one-storm-out independent test results. The significance of the correlations was also tested. The ′ in the Table means significance.

The correlation coefficients are lower, as expected, but some significance remains. There is, apparently, significant information about storm motion out to at least 24 hours in the temperature data.

Durning this one-storm-out independent test the mean and standard deviation of the least squares solution of the regression coefficients (C matrix) were calcualted. The mean values of the regression coefficients out to 24 hours are shown for the 250-100 mb layer and for the three layer combination in Tables 4.11 and 4.12. The ratios of the standard deviations to the means of each regression coefficient are shown in Table 4.13 and 4.14.

It is found that for predictands with significant correlation

Table 4.10 Correlation coefficients from the one-storm-out independent test

	250-100 mb		3-layer combination	
	12 hour	24 hour	12 hour	24 hour
X	0.44′	0.55′	0.45′	0.62′
Y	0.29	0.24	0.35′	0.19
D	0.39′	0.43′	0.36′	0.49′
S	0.22	0.42′	0.33′	0.36′
I	0.14	0.10	0.14	0.10

Table 4.11 The mean regression coefficients for 250-100mb, 24 hour forecasts

	1-st	2-nd	3-rd	4-th	5-th
X	0.20	0.01	0.18	0.02	0.02
Y	0.10	0.03	0.02	0.05	0.04
D	4.42	0.98	3.83	0.18	1.21
S	0.79	0.20	0.30	0.14	0.27
I	2.33	1.28	1.04	1.11	0.07

units: X, Y = degrees latitude/K.

D = degrees/K. S, I = knots/K.

Table 4.12 Same as Table 4.11 except for the 3-layer combination

	1-st	2-nd	3-rd	4-th	5-th	6-th
X	0.16	0.30	0.06	0.12	0.05	0.04
Y	0.09	0.07	0.10	0.05	0.01	0.03
D	2.41	7.36	2.76	2.86	1.53	0.36
S	0.16	0.64	0.61	0.11	0.07	0.25
I	1.49	1.42	1.66	0.76	0.64	0.82

Table 4.13 The ratio of the standard deviation to the mean of the regression coefficients for 250-100mb, 24 hour forecasts

	1-st	2-nd	3-rd	4-th	5-th
X	0.11	1.60	0.05	0.40	0.22
Y	0.17	0.45	0.41	0.12	0.11
D	0.16	0.43	0.08	0.47	0.08
S	0.09	0.22	0.21	0.19	0.07
I	0.16	0.41	0.19	0.20	2.58

Table 4.14 Same as Table 4.13 except for the 3-layer combination

	1-st	2-nd	3-rd	4-th	5-th	6-th
X	0.12	0.05	0.19	0.10	0.12	0.10
Y	0.28	0.27	0.12	0.21	0.49	0.22
D	0.34	0.06	0.17	0.13	0.14	0.37
S	0.50	0.15	0.08	0.59	0.33	0.13
I	0.49	0.32	0.26	0.34	0.30	0.19

coefficients, the ratios of the standard deviations to the means of the regression coefficients, with one exception, are small, which indicates that the regression equations are quite stable.

C. Physical Interpretation

Perhaps the best way to interpret these results physically is through the D matrix. Given a set of observations of satellite-estimated mean layer temperature deviations in a square domain centered on a tropical cyclone, one produces a forecast simply by multiplying by (taking the inner product with) the D matrix (Eq. 3.8). For this reason, the D matrix has been called a relative importance map (Hunter et al., 1981). The relative importance maps for 12 and 24 hour forecasts using the 250-100 mb layer and the three layer combination as predictors are shown in Fig. 4.7 through 4.10. The presentation is such that a positive (negative) temperature anomaly where the relative importance map is positive (or a negative (positive) temperature anomaly where the relative importance map is negative) contributes to a positive (negative) anomaly in the predictand; i.e. a right (left) turn, an increase (decrease) in speed, a displacement right (left) of persistence, or a displacement ahead of (behind) persistence.

Fig. 4.7. suggests that for 12 hour speed increase, one wants to see cold temperatures to the left and warm temperatures to the right such that the thermal wind is in the direction of storm motion up to 250 mb. For direction change, the storm should be heading into an area of strong thermal winds perpendicular to the storm track. X and Y are consistent with direction change and speed change.

The 250-100 mb relative importance map is more difficult to interpret physically because of its location near the tropopause. A possible

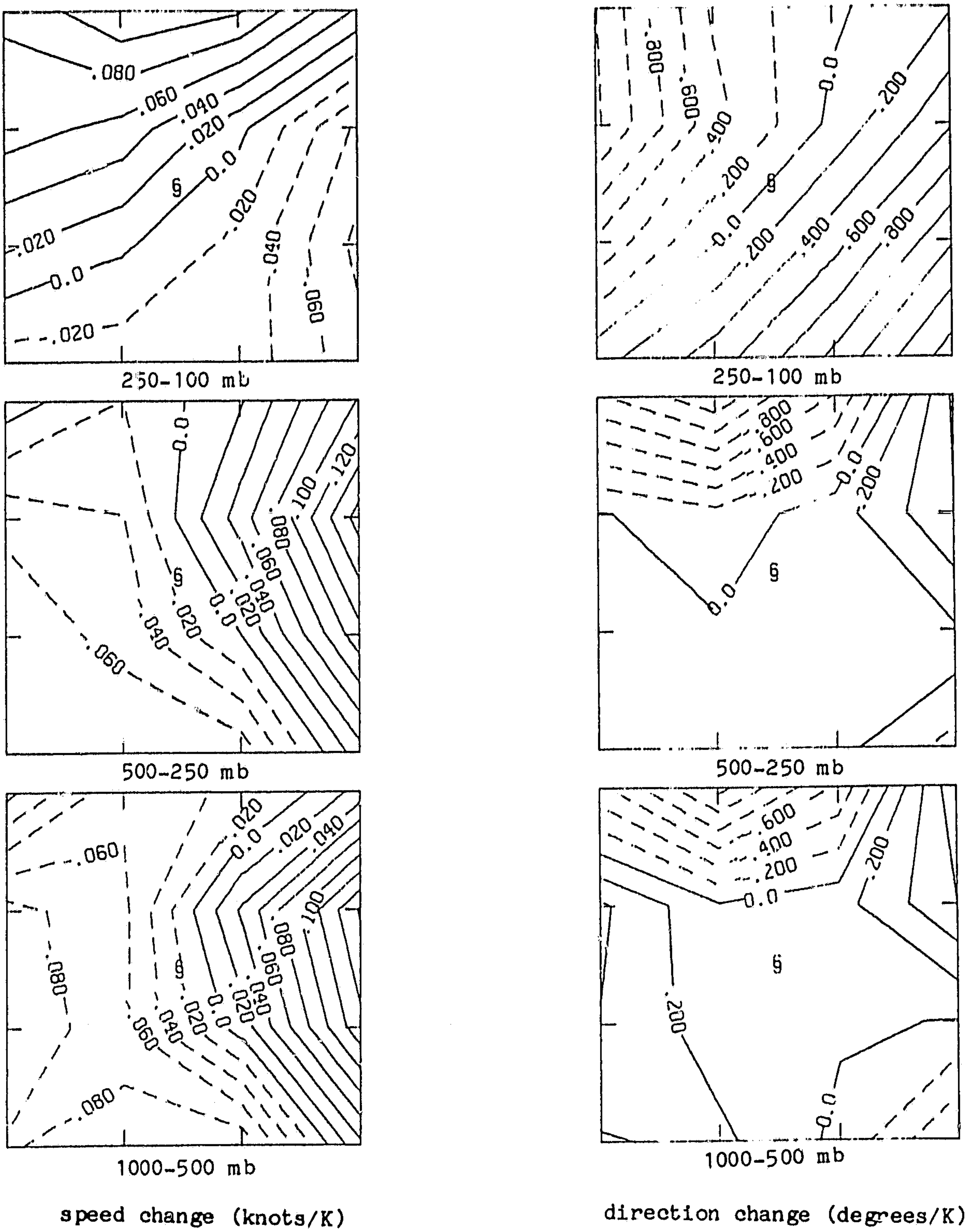


Fig. 4.7. The relative importance maps for the 3-layer combination, 12 hour forecasts.

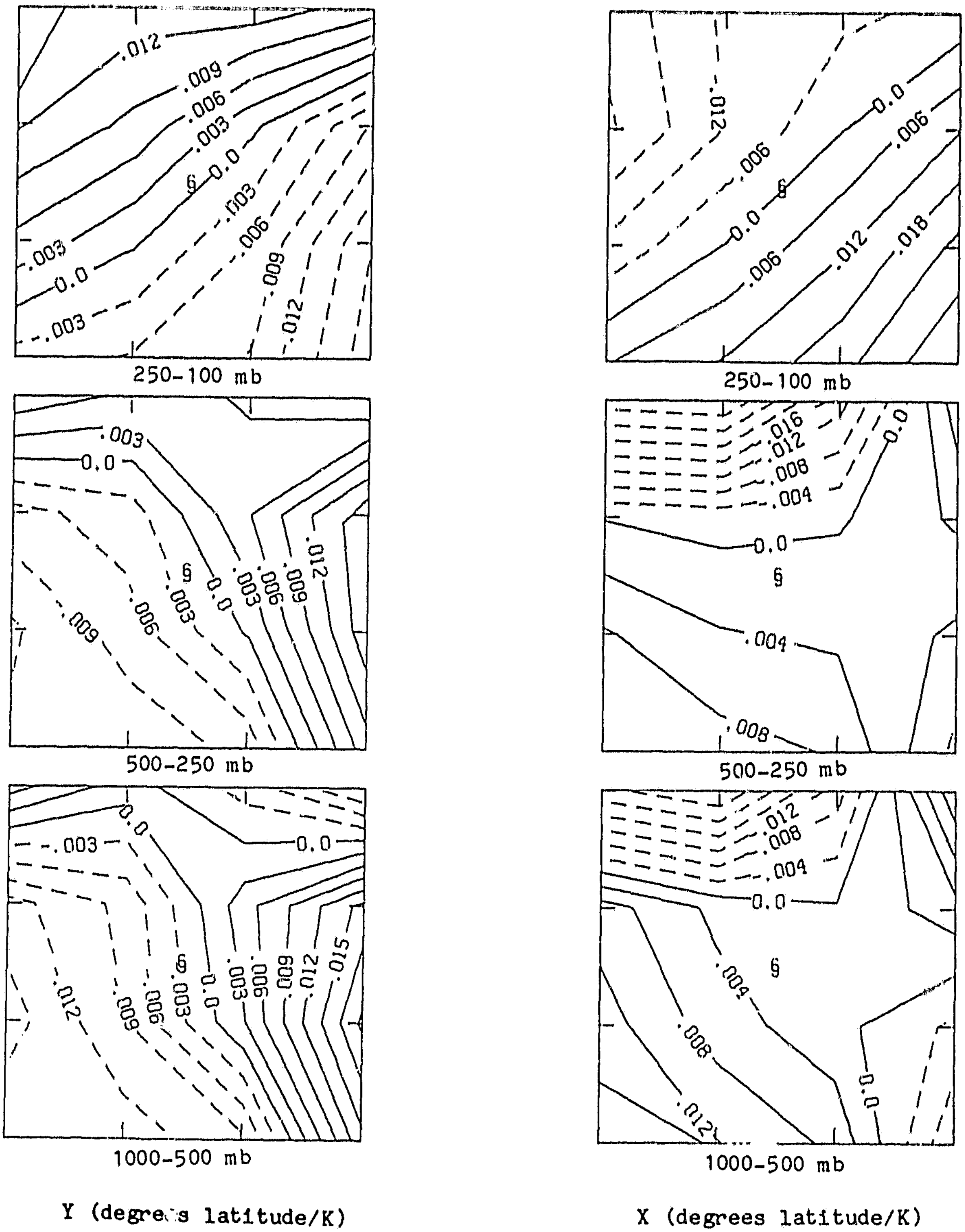


Fig. 4.7. Continued.

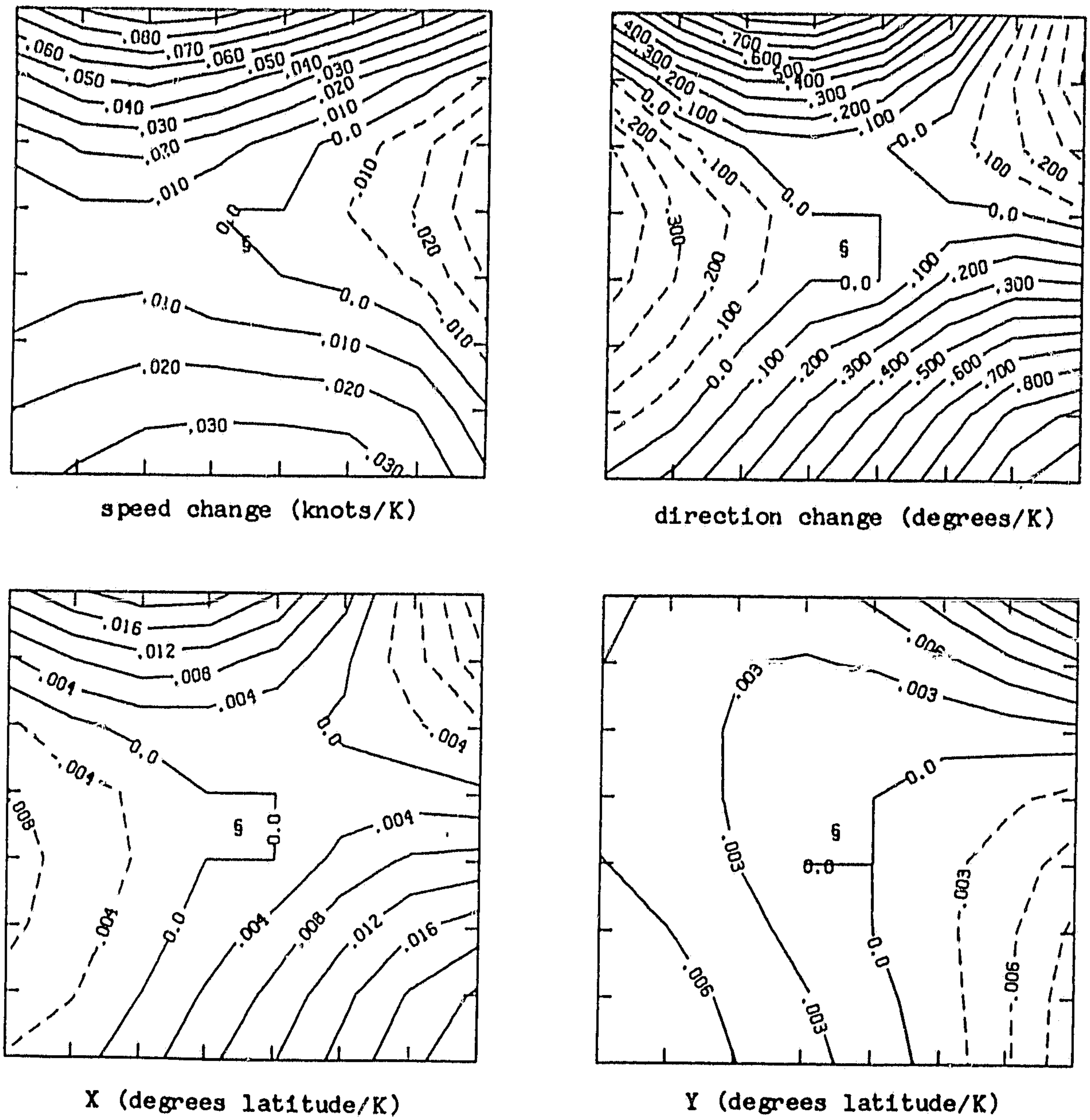


Fig. 4.8. The relative importance maps for the 250-100 mb, 12 hour forecasts.

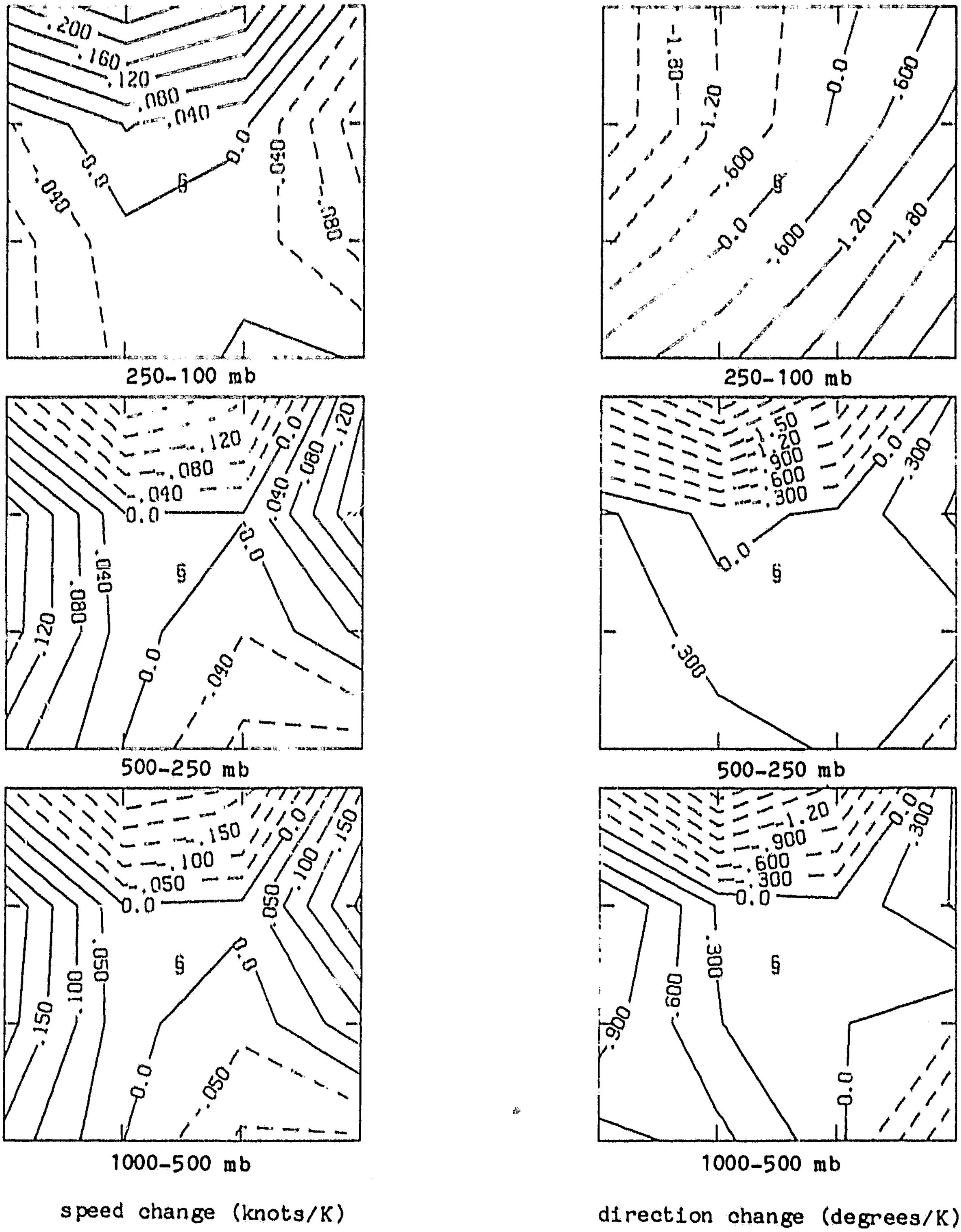
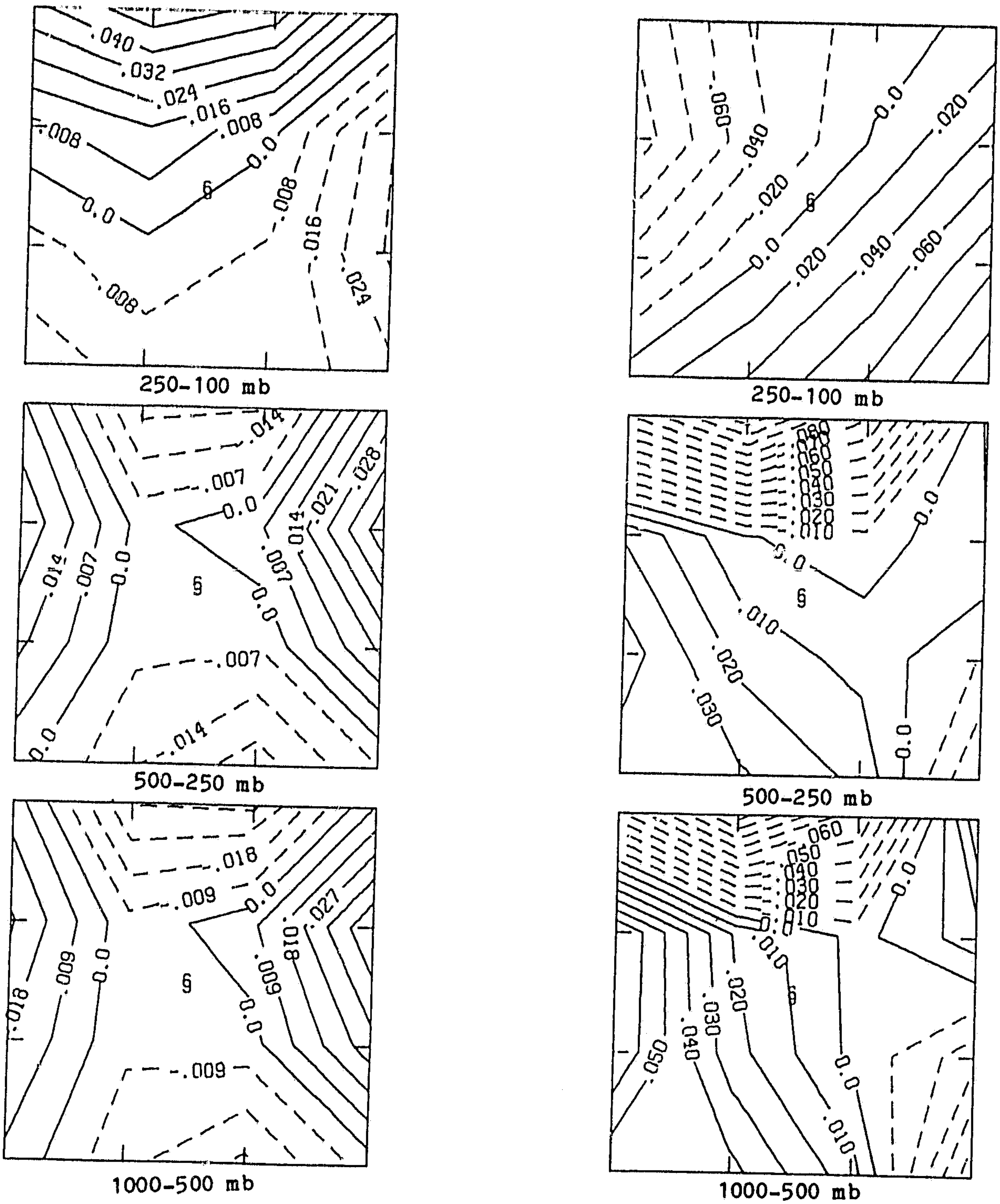


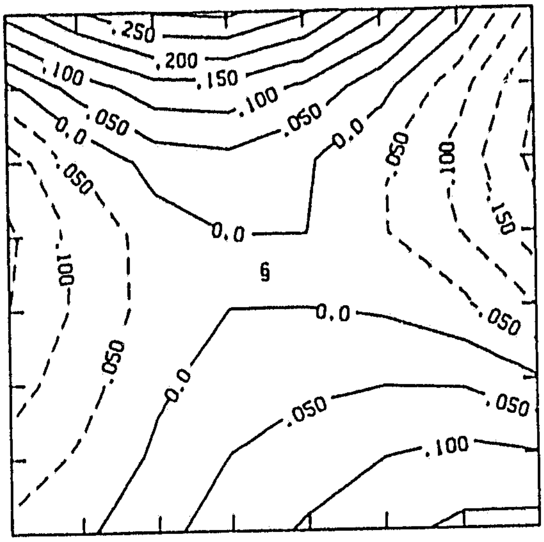
Fig. 4.9. The relative importance maps for the 3-layer combination, 24 hour forecasts.



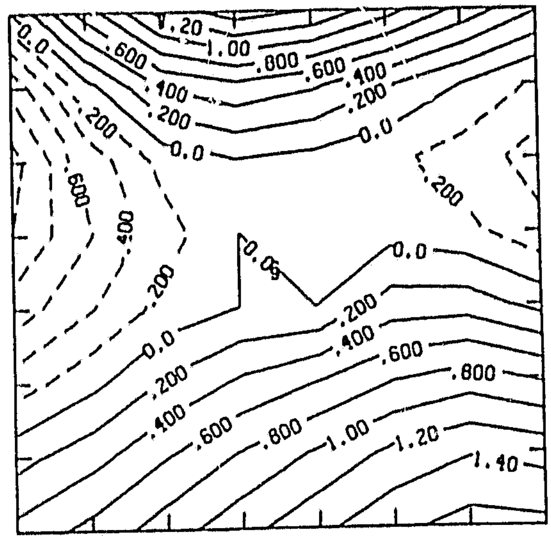
Y (degrees latitude/K)

X (degrees latitude/K)

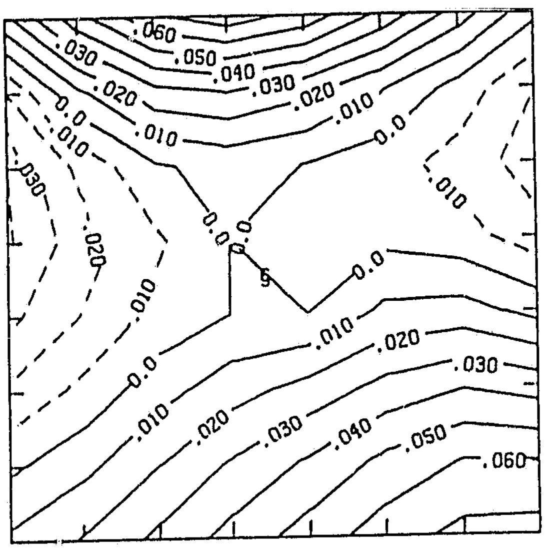
Fig. 4.9. Continued.



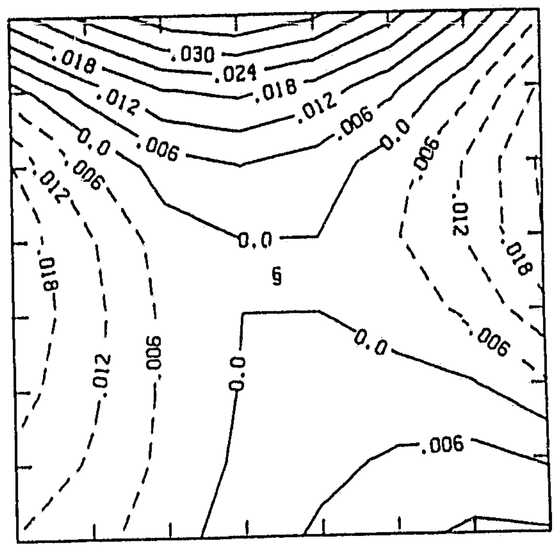
speed change (knots/K)



direction change (degrees/K)



X (degrees latitude/K)



Y (degrees latitude/K)

Fig. 4.10. The relative importance maps for the 250-100 mb, 24 hour forecasts.

interpretation is as follows: Suppose the storm is approaching a midtropospheric trough. One would expect the storm to increase its speed and turn right. This is consistent with the relative importance maps if one recalls that midtropospheric troughs are overlain by warm stratospheric temperatures (Palmén and Newton, 1969). The reason that the 250-100 mb layer has the most signal may be because the tropopause level has the largest temperature fluctuations (Oort and Rasmusson, 1971). The temperature patterns at upper levels may simply be a reflection of conditions (such as winds) in the troposphere which actually steer the storm.

The relative importance maps for 24 hour direction change and distance right of persistence are nearly identical with those for 12 hour forecasts. Those for speed change and distance ahead of persistence are quite different from the 12 hour maps. Indeed they are very similar to the maps for direction change and distance right of persistence, which implies that speed change is coupled with direction change at 24 hours. They may both be caused by the same physical mechanism.

Physical interpretation of statistical results is difficult, especially when the correlation coefficients we get are not very large. The largest one is 0.67 which also means more than 50% variance is left unexplained. The interpretations offered here are not the only possibilities. The relative importance maps are included in part so that readers may construct their own interpretations.

CHAPTER V

CONCLUSIONS

The main conclusion from this work is that there appears to be significant information about changes in tropical cyclone motion in satellite-estimated mean layer temperatures. The best forecast paramaters are distance right of persistence and direction change. The best levels for forecasting these parameters are upper levels. The distance ahead of persistence and speed change are less well predicted by the temperature data. Finally, very little significance was found in forecasts of intensity change based on the mean layer temperatures.

The results are encouraging enough to suggest that they be explored further. First, the technique should be tried with data from newer, more accurate satellite instruments such as the Microwave Sounding Unit (MSU) on board the TIROS-N series satellites and/or the VISSR Atmospheric Sounder (VAS) on the GOES-4 and GOES-5 satellites. Second, it would be interesting to modify the data slightly. One might, for example, attempt to use the brightness temperatures alone to make a forecast, thus eliminating retrieval errors, or one might convert the mean layer temperatures to heights using a surface pressure analysis, thus providing a more direct comparison with steering forecasts. Third, modification of the grid would be interesting. In light of the success of the three layer combination predictor with coarse horizontal resolution a larger, coarser grid should be tried, as should an unrotated grid (always directed North) which would permit easier comparison with previous work. Finally, methods for combining the satellite sounding information with other forecast techniques should be explored. One can envison combining a climatology plus persistence (CLIPER) type forecast (Neumann, 1972) with satellite temperature information, which would indicate likely deviations from pure CLIPER forecasts. Of course the ultimate goal should be to combine satellite observations with conventional observations in such a way that each data type would contribute as best it could to an analysis of the true state of the atmosphere. Such analysis techniques are active research topics, and when complete they will make possible better forecasts using numerical models and better theoretical understanding of the processes which are responsible for storm motion.

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