On the Potential Use of Satellite Sounder Data in Forecasting Tropical Cyclone Motion

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ABSTRACT

Although many prediction schemes are available, tropical cyclone track forecast errors are still unacceptably large. A primary difficulty is that tropical cyclones and their environments are poorly observed by conventional data networks. Satellite sounders, however, routinely provide numerous observations near these storms. Mean layer temperatures from the Scanning Microwave Spectrometer (SCAMS) on board the Nimbus-6 satellite are decomposed using empirical orthogonal functions, and the expansion coefficients are related to deviations from persistence track forecasts. Based on multiple correlation coefficients it appears that upper-level (250–100 mb) temperatures contain significant information about the right-angle error of the persistence forecast location. Temperatures from the 1000–500 mb layer seemed to contain little forecast information. Implications of these results for further work are offered.

1. Introduction

A most important problem facing the tropical meteorologist is the prediction of the motion (or tracks) of tropical cyclones. Over the years an enormous amount of work on this problem has been done, with the result that mean track forecast errors have gradually declined. Today, the mean errors in the Atlantic, for example, are about 200, 450 and 700 km at 24, 48 and 72 h, respectively (Neumann and Pelissier, 1981).

These errors, however, are still unacceptably large—nearly one half of the mean distance traveled by the storm during the forecast period. In addition, Neumann (1981) found that 24 h track forecast accuracy is tending toward a plateau and has not improved much since 1970. He attributed most of the problem to "a gradual erosion in the ability . . . to assess environmental steering forces." Today there are fewer ocean station vessels and midlevel aircraft reports than there were in the 1960s when track forecasting ability substantially improved over what it was in the 1950s (Dunn *et al.*, 1968). Neumann goes on to state ". . . the only way to foster improved tropical cyclone [track] forecasting is to improve on the ability to assess environmental steering forces."

Tropical cyclones are steered by the mean tropospheric winds, and middle levels are most representative of the mean flow (e.g., Chan and Gray, 1982). Unfortunately, midlevel wind observations are not easily obtained in the tropics. It was hoped that cloud-tracked winds from geostationary satellite data would help, but most trackable clouds in the tropics are at upper and lower levels. Few clouds are trackable at middle levels (Hubert, 1979). Other currently available satellite data, however, may contain information related to steering flow.

Because the atmosphere is hydrostatic, and winds are nearly geostrophic, one might expect satellite soundings to be indirectly related to steering flow. Chan *et al.* (1980) examined satellite soundings around several tropical cyclones and concluded that mean 1000–250 mb temperature fields might be useful in track forecasting. The purpose of the present work was to apply statistical techniques to determine how much information about the future motion of tropical cyclones is contained in fields of satellite soundings. Our purpose was not to develop a new forecasting technique, of which there are already many. Instead, we wanted to determine whether satellite soundings ought to be considered for inclusion as direct predictors in future forecasting schemes, rather than indirectly through the use of satellite-enhanced analyses.

2. Data

Data from the Scanning Microwave Spectrometer (SCAMS) on board the Nimbus 6 satellite were employed in this study. A microwave instrument was chosen because soundings can be retrieved even in the presence of clouds. A similar instrument called the Microwave Scanning Unit (MSU) is on the currently operational TIROS-N series satellites. The data from an infrared sounder (e.g., from the GOES satellites) could be used if there were sufficient breaks in the clouds. SCAMS was a five-channel instrument

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which nominally sensed radiation at 22.235, 31.65, 52.85, 53.85 and 55.45 GHz. Data from the first two channels were used to estimate integrated liquid water and water vapor over the ocean. The last three channels are within the 5 mm oxygen absorption band and were used to retrieve atmospheric temperatures. The noise equivalent ΔT for the last three channels provides a rough estimate of the error in the retrieved temperatures: about 0.5 K. The horizontal resolution was 145 km at nadir but degraded to 220 × 360 km (measured parallel to and perpendicular to the satellite's track, respectively) at the maximum scan angle (±43.2°). The orbit and scan geometries were such that the entire earth was viewed twice per day (Staelin *et al.*, 1975a): once near local noon and once near local midnight (except near the poles which were more frequently observed). A maximum of about 70 000 soundings were made each day. Atmospheric temperatures were retrieved from SCAMS radiances at the Massachusetts Institute of Technology by Staelin *et al.* (1975a); these data are archived at the National Space Science Data Center in Greenbelt, Maryland. Because retrieved temperatures for deep layers are more accurate than temperatures at a particular level (Staelin *et al.*, 1975b; Schlatter, 1981), and because Chan *et al.* (1980) indicated that deep layer temperatures might be useful for motion studies, the temperatures used in this study were mean temperatures for the 1000–500, 500–250 and 250–100 mb layers. Although microwave soundings are nearly unaffected by clouds, precipitation can cause errors. Therefore, soundings with liquid water contents (determined from SCAMS channels 1 and 2) greater than 0.5 kg m^{-2} were discarded (Staelin *et al.*, 1975b).

This study concentrated on the western North Pacific during July 1975 through April 1976, which is nearly the entire period for which the SCAMS instrument was operational. Best track data for the fifteen typhoons and eleven tropical storms which occurred during this period were taken from the 1975 and 1976 Annual Typhoon Reports (Joint Typhoon Warning Center, 1975, 1976). In order to form a homogeneous data set, portions of a storm track during which 1) the storm had intensity less than 34 kt, 2) its center was north of 30°N, or 3) a loop turn was executed, were eliminated from the sample. It was felt that separate forecast techniques would be necessary for these cases. In all, there were 67, 58, 50 and 40 position observations for 12, 24, 36 and 48 h forecasts, respectively.

3. Analysis

To relate the mean layer temperatures retrieved from SCAMS data to future storm locations, we chose to use a simple but very powerful analysis technique involving empirical orthogonal functions (EOFs), which was introduced to meteorology by Lorenz (1956). The retrieved temperatures were objectively analyzed with a modified Cressman scan analysis (Inman, 1970) onto a 10 × 10 grid using a stereographic horizon map projection (Shenk *et al.*, 1971). The grid spacing was 4° latitude (444 km), the storm was at the center of the grid, and the top of the grid was oriented in the direction of storm motion. The outer rows of grid points were then discarded (to eliminate edge effects) leaving an 8 × 8 grid (Fig. 1). Note that the grid spacing is larger than the resolution of the satellite data even at the maximum scan angle. About 1000 soundings were processed for each data field.

The basic fields which we analyzed were the mean temperatures for the 1000–500, 500–250 and 250–100 mb layers. These temperatures came directly from the SCAMS data tapes. Because the atmosphere is hydrostatic, these temperatures are proportional to the thicknesses of the layers. If the variation of surface pressure, which is small in the tropics, is ignored, the 1000–500 mb mean layer temperature gives an estimate of the 500 mb height. The 1000–500 mb temperature, then, is related geostrophically to mid-level winds. In addition, we determined the pressure-weighted mean of the 1000–500 and 500–250 mb temperatures, to yield the mean 1000–250 mb temperature. These are the data used by Chan *et al.* (1980); they are related to the winds at 250 mb.

To remove latitudinal and seasonal effects, at each time period the objectively analyzed temperatures at the four grid points closest to the storm center were

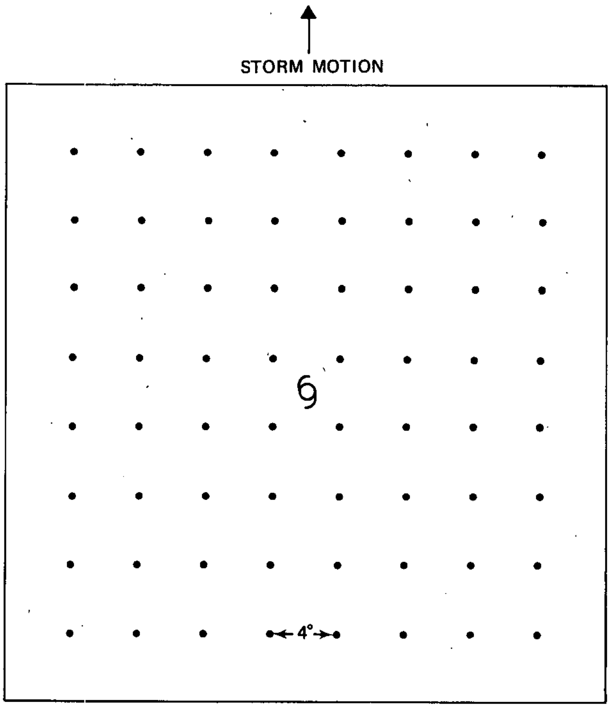
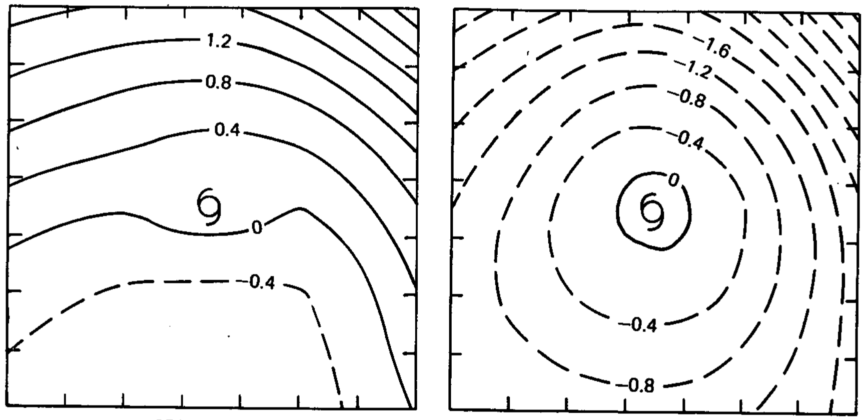


FIG. 1. Analysis grid.

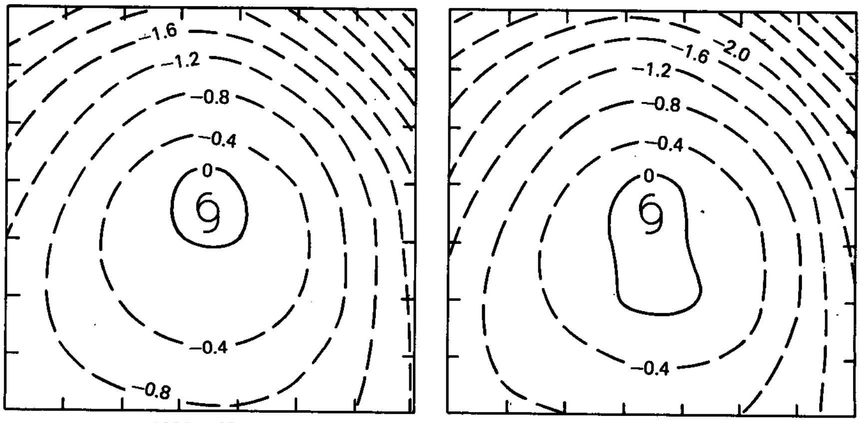
averaged, and then the average was subtracted from each of the 64 grid points. The resulting time-averaged fields are shown in Fig. 2. Due to the above process, the zero line is close to the center of each mean field. As expected, these storms are warm core below 250 mb. Above 250 mb, the reverse pole-to-equator temperature gradient in the stratosphere is evident. The final step before performing the EOF analysis was to calculate temperature deviation fields by subtracting the time-averaged fields (Fig. 2).

The EOFs were calculated in the manner described by Kutzbach (1967). When the EOFs are calculated, the number of EOFs equals the number of grid points (64 in this case). Not all of the EOFs contain significant information, however. The most information is contained in the EOFs with the largest eigenvalues. Preisendorfer and Barnett (1977) have devised a method for determining how many of the EOFs are statistically significant. Using their method, we found that the first five EOFs, which collectively accounted for more than 90% of the variance, were statistically significant at the 95% level. We discarded the remaining EOFs.

The significant EOFs are shown in Fig. 3. There is some disagreement on whether EOFs can be interpreted as map patterns (Richman, 1981) which influence the storm's motion. However, it can be seen in Fig. 3 that the first EOF, which explains about one half of the variance in the temperature data and which is most strongly related to storm motion, appears to represent a situation in which the storm is in or approaching a large temperature or thickness gradient oriented obliquely to the storm track. To the extent that the temperature fields are related to winds, one could say that the storm is in or approaching an area of winds which would tend to cause the storm to turn and change speed. (The sign of the change is dependent on the sign of the expansion coefficient. The magnitude of the change is dependent on the magnitude of the expansion coefficient.) The third EOF of the 250–100 mb temperature field is also related to storm motion (see below). This EOF, which generally indicates an inward temperature gradient, may be related to storm intensity. The other EOFs, which are less strongly related to storm motion, may represent map patterns which modify the influ-



250 – 100 mb   500 – 250 mb



1000 – 250 mb   1000 – 500 mb

FIG. 2. Time average of normalized SCAMS mean layer temperatures (K).

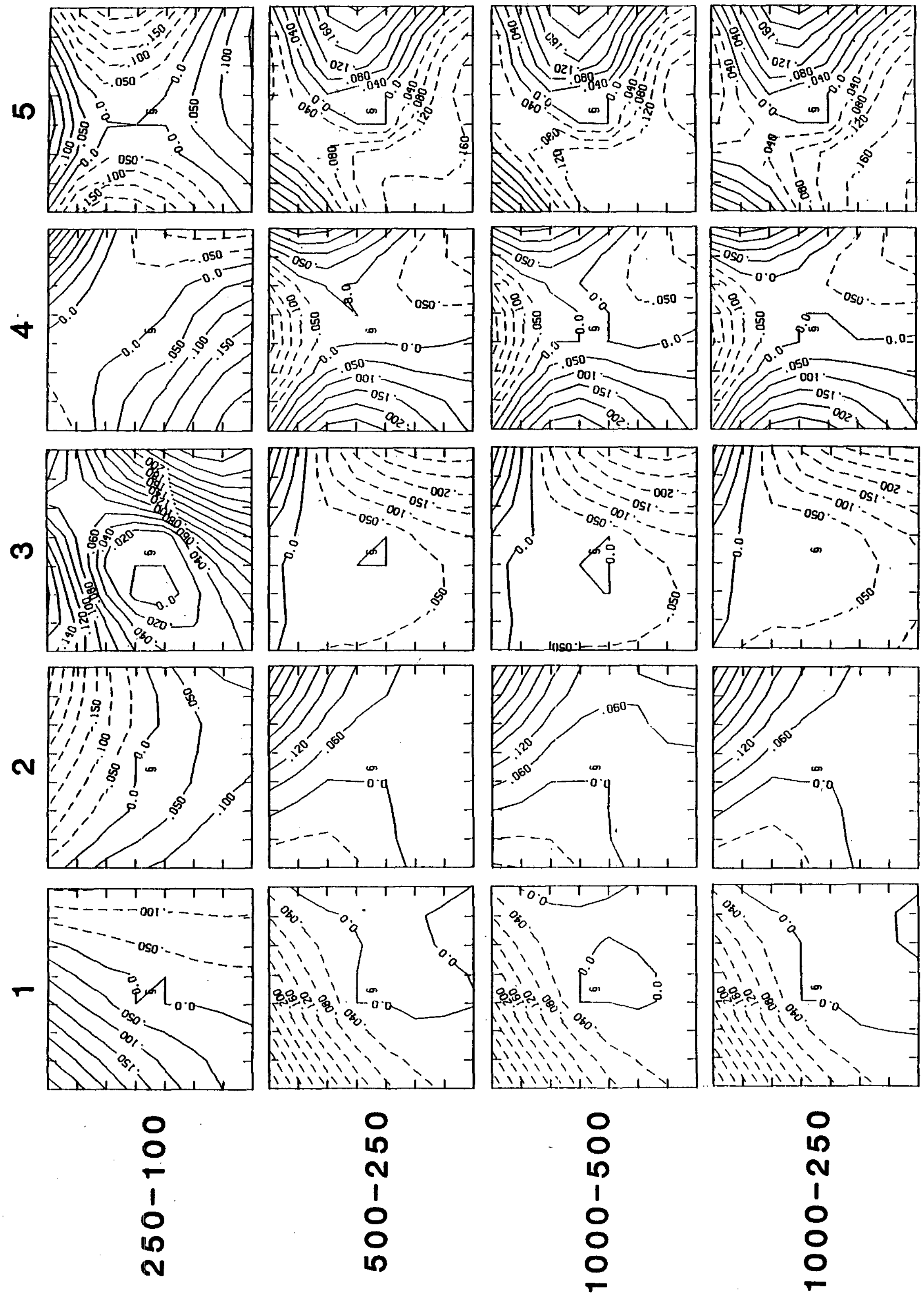


FIG. 3. Significant EOFs of the mean layer temperature fields.

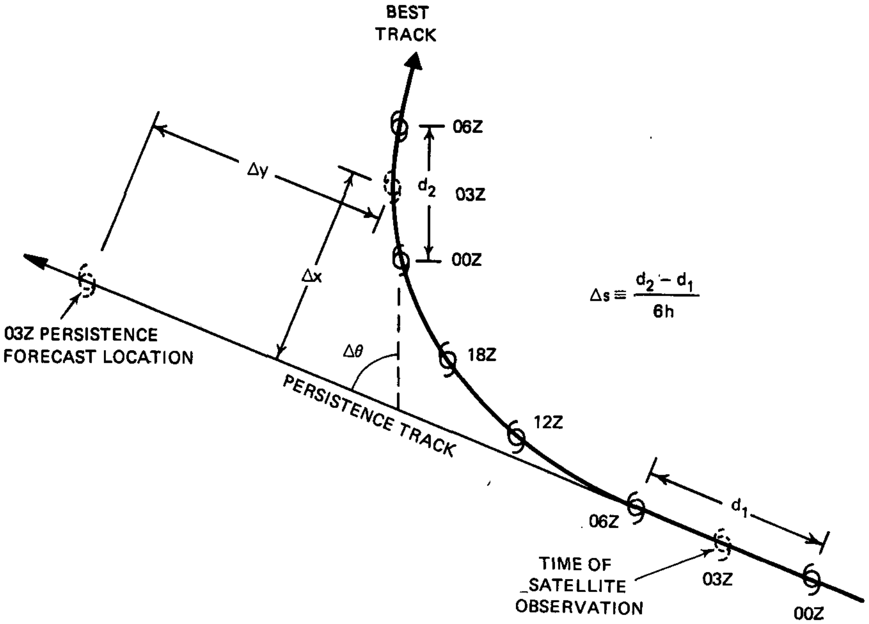


FIG. 4. Example of motion parameters for a 24 h forecast.

ence of the other EOFs. To relate the motion of the storms to the EOFs, the observed temperature deviation fields are expanded by taking the inner product with the EOFs. The resulting expansion coefficients can be used as predictors. Shaffer and Elsberry (1982) recently described a statistical-climatological track forecasting scheme using EOF expansion coefficients of 500 mb height fields obtained from Northern Hemisphere analyses. They developed the prediction equations by performing a stepwise screening regression (Dixon and Brown, 1979, pp. 367–460) on the expansion coefficients and past positions of the storm. Because we were not trying to develop an independent forecasting scheme, but only to assess the information content of the retrieved temperatures, we took a simpler approach.

Persistence often gives a good forecast, especially when storms are south of 30°N. We decided, therefore, to attempt to use the EOF expansion coefficients to forecast deviations from simple persistence. Nimbus 6 passed the western North Pacific near 0300 and 1500 GMT. Best track information (Joint Typhoon Warning Center, 1975, 1976) was given at 0000, 0600, 1200 and 1800 GMT. The location of the storm at the time of satellite observation was interpolated from the best track locations (Fig. 4). The persistence track was defined as the linear extrapolation of the storm's position from the two best track locations straddling the satellite observation. The persistence direction was used to orient the objective analysis grid discussed above. Four parameters describing deviations from persistence were defined for use as predictands. They were (see Fig. 4): 1) speed change Δs, defined as the difference in speeds during the 6 h periods surrounding the verifying time and the initial time; 2) direction change $\Delta\theta$, defined as the difference in storm heading during the same 6 h periods; 3) distance right of persistence, Δx, defined as the perpendicular distance of the storm from the persistence track; and 4) distance ahead of persistence, Δy, defined as the distance ahead of the persistence forecast location measured parallel to the persistence track. (Note that in Fig. 4 Δy is negative.) For reference, the means and standard deviations of the predictands are listed in Table 1.

To relate the temperature fields to storm motion, the predictands (Δx, Δy, Δs, $\Delta\theta$) were regressed against the EOF expansion coefficients of the temperature fields using the multiple regression equation

$$\hat{z}(t + \Delta t) = z_0(\Delta t) + \sum_{i=1}^{5} a_i(\Delta t)c_i(t), \qquad (1)$$

TABLE 1. Predictand statistics.

Predictand	Forecast period			
	12 h	24 h	36 h	48 h
Δx: Mean (km)	19	54	115	234
Std. dev. (km)	46	101	195	296
Δy: Mean (km)	31	99	174	249
Std. dev. (km)	41	105	178	253
$\Delta\theta$: Mean (deg)	4	9	16	24
Std. dev. (deg)	24	34	43	47
Δs: Mean (m s^{-1})	0.48	0.92	1.64	1.17
Std. dev. (m s^{-1})	1.90	2.86	3.44	3.48

where $\hat{z}$ is the forecast value, $z_0(\Delta t)$ is the mean forecast value (Table 1) for Δt forecasts ($\Delta t = 12$, 24, 36 or 48 h), $a_i(\Delta t)$ is the ith regression coefficient for Δt forecasts, and $c_i(t)$ is the expansion coefficient of the ith EOF of the temperature field at time t. Basically, the forecast of a deviation from persistence is a weighted average of the EOF expansion coefficients, which represent the important information in the temperature fields, plus a mean forecast. No screening was done; all of the five significant EOFs were used in the regression equations.

4. Results

Our results will be presented in terms of multiple correlation coefficients (Table 2). Those who wish to do so may calculate the standard error of estimate using the data in Tables 1 and 2, but a word of caution is in order. By eliminating difficult forecast situations, like looping storms from our sample, we lowered the standard deviation of our predictands. Also, we used best track positions rather than operational positions, thus artificially improving our forecasts. The standard error of estimate should not be directly compared, therefore, with the official track forecast error estimates noted in Section 1. All of the multiple regression coefficients listed in Table 2 have been corrected for shrinkage (i.e., for the number of predictors) by the Wherry formula (Wherry, 1931; Lorenz, 1977).

One way to ascertain whether the retrieved temperature fields contain significant information on the motion of tropical cyclones is to determine the statistical significance of the multiple correlation coefficients. When doing this, care must be taken not to overestimate the significance. Our data sample is not strictly independent; it is comprised of 12 h observations. A method often used to correct for the correlation between observations taken at 12 h intervals is to divide the sample size by 3 (Neumann, 1979). The critical (95%) multiple correlation coefficients, then, for 12, 24, 36 and 48 h forecasts are 0.423, 0.456, 0.497 and 0.553, respectively (Beyer, 1971). The correlation coefficients in Table 2 which are greater than these critical values are marked with an asterisk.

Table 2 seems to indicate that there is significant information about storm motion in the temperature fields out to 36 h. The best forecast parameter is Δx, or the right-angle error of the persistence forecast; however, the temperatures may yield some information about speed change Δs and direction change $\Delta\theta$, at least at 24 h. A disturbing aspect of these correlation coefficients is that some of them increase between 12 and 24 h. Usually such correlation coefficients decrease with time. We checked the 12 h forecasts for the nine storms which were not included in the 24 h forecasts and found that all were decaying storms for which the regression equations yielded poor forecasts. This may indicate that the data should be stratified by the stage in the storm's life cycle.

The most interesting result in Table 2 is that the only predictor field which contains significant information about storm motion is 250–100 mb temper-

TABLE 2. Multiple correlation coefficients.

	Predictor fields			
Predictand	1000–500 mb	500–250 mb	250–100 mb	1000–250 mb
12 h forecasts ($N = 67$):				
Δx	0.40	0.38	0.48*	0.40
Δy	0.40	0.36	0.36	0.38
$\Delta\theta$	0.21	0.12	0.42	0.19
Δs	0.33	0.30	0.29	0.32
24 h forecasts ($N = 58$):				
Δx	0.31	0.28	0.58*	0.28
Δy	0.13	0.05	0.25	0.10
$\Delta\theta$	0.13	0	0.50*	0
Δs	0.41	0.38	0.46*	0.40
36 h forecasts ($N = 50$):				
Δx	0.30	0.18	0.56*	0.30
Δy	0	0	0.20	0
$\Delta\theta$	0	0	0.32	0
Δs	0.39	0.35	0.42	0.39
48 h forecasts ($N = 40$):				
Δx	0.19	0	0.43	0
Δy	0	0	0	0
$\Delta\theta$	0.10	0	0.36	0
Δs	0	0	0.10	0

* Correlation coefficients greater than critical values (see text).

ature. *A priori*, the 1000–500 mb temperatures would be expected to be most significant. Since satellite soundings are usually most accurate at middle levels (e.g., Gruber and Watkins, 1982), it is unlikely that this result is caused by errors in the retrieved temperatures. We also doubt that it is an artifact of the analysis scheme, although this cannot be completely ruled out. One possibility (pointed out by a reviewer) is that the regression equations for the 250–100 mb layer are making forecasts based on the strength of the storm. Stronger storms are colder than weaker storms in the uppermost troposphere, and stronger storms have a greater probability of turning to the right. This suggestion is supported by the regression coefficients for 24 h forecasts using 250–100 mb temperatures shown in Table 3. The two largest regression coefficients in the Δx equation are for EOFs 1 and 3. As mentioned above, EOF 3 could be viewed as indicating storm strength. Another possibility is that changes in the tropopause level associated with midlatitude troughs, which often cause recurvature, may be reflected in the satellite-estimated mean 250–100 mb temperature. This suggestion is supported by the magnitude of the Δx regression coefficient for EOF 1.

Our results are consistent with those of Pike (1984) who regressed Atlantic tropical cyclone motion against heights and thicknesses derived from National Meteorological Center (NMC) analyses. Pike found that when only thicknesses were used to forecast storm motion, the 300–100 mb layer gave the best results. However, he also found that midlevel heights were superior to thicknesses for motion forecasts.

The best way to assess the amount of information on storm motion which is contained in the retrieved temperature fields is through a strictly independent test of the regression equations. Because our sample of observations was small, however, no points could be reserved for an independent test. Instead, a semi-independent test called a storm-out independent test (Hunter *et al.*, 1981) was employed. If all observations of a single storm are removed from the sample, the first few EOFs change very little. The storm-out procedure uses EOFs from all of the storms. One storm (all observations) is deleted from the data base, and the regression equations are developed. These equations are then used to make forecasts for the deleted storm. This process is repeated cyclically until all of the storms are used as "independent" data.

Table 3. Regression coefficients for 24 h forecasts using 250–100 mb temperature fields. Predictors are defined in Fig. 4.

Predictand	EOF 1	2	3	4	5
Δx (km K^{-1})	22	1.1	20	2.2	2.2
Δy (km K^{-1})	11	3.3	2.2	5.6	4.4
$\Delta\theta$ (deg K^{-1})	4.4	0.98	3.8	0.18	1.2
Δs (m s^{-1} K^{-1})	0.41	0.10	0.15	0.07	0.14

Table 4. Multiple correlation coefficients for the storm-out independent test using 250–100 mb temperatures as predictors. The asterisks indicate significance as in Table 2.

Predictand	Forecast period 12 h	24 h
Δx	0.44*	0.55*
Δy	0.29	0.24
$\Delta\theta$	0.39	0.43
Δs	0.22	0.42

Storm-out correlation coefficients for 12 and 24 h forecasts made using the 250–100 mb temperatures are shown in Table 4, where the asterisks indicate significance as in Table 2. The correlation coefficients are slightly lower, in some cases, than those in Table 1, but they still retain a high level of significance.

5. Discussion

In this study we attempted to determine whether satellite soundings might be useful in forecasting tropical cyclone motion. We found apparently significant correlations between mean 250–100 mb temperature fields and deviations from the persistence storm track. Temperatures at other levels did not produce significant correlations. Because tropical cyclone track forecasting is an important meteorological problem, and because satellite soundings are one of the only sources of "new" data for the data-sparse tropical oceans, the finding of significant correlations justifies further investigation. First, data from newer, more accurate satellite sounders such as the MSU on the TIROS-N series satellites or the VAS sounder on the GOES satellites should be employed. Second, based on the work of Pike (1984), heights, estimated from satellite-derived thicknesses and surface pressure analyses, should be regressed against tropical cyclone motion. Third, motion forecasts made with and without satellite soundings need to be compared to see if the satellite data add significantly to information already available. Finally, an attempt to use retrieved temperatures and/or heights as predictors in a statistical–climatological scheme like that of Shaffer and Elsberry (1982) seems warranted.

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