NASA

Technical Memorandum 79645

Predicting Tropical Cyclone Intensity Using Satellite Measured Equivalent Blackbody Temperatures of Cloud Tops

(NASA-TM-79645) PREDICTING TROPICAL CYCLONE INTENSITY USING SATELLITE MEASURED EQUIVALENT BLACKBODY TEMPERATURES OF CLOUD TOPS (NASA) 42 p HC A03/MF A01 CSCL 04B
N79-10670
Unclas
G3/47 37152

R. Cecil Gentry, Edward Rodgers, Joseph Steranka, William E. Shenk

September 1978

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

TM 79645

PREDICTING TROPICAL CYCLONE INTENSITY USING SATELLITE MEASURED EQUIVALENT BLACKBODY TEMPERATURES OF CLOUD TOPS

R. Cecil Gentry*
Edward Rodgers**
Joseph Steranka*
William E. Shenk**

September 1978

*General Electric Space Division (MATSCO), Beltsville, Maryland 20705
**Laboratory for Atmospheric Science (GLAS) NASA/GSFC, Greenbelt, Maryland 20771

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

PREDICTING TROPICAL CYCLONE INTENSITY USING SATELLITE MEASURED EQUIVALENT BLACKBODY TEMPERATURES OF CLOUD TOPS

R. Cecil Gentry*
Edward Rodgers**
Joseph Steranka*
William E. Shenk**

ABSTRACT

A regression technique has been developed to forecast 24-hour changes of the maximum winds for weak (maximum winds $\leq$ 65 kt) and strong (maximum winds > 65 kt) tropical cyclones by utilizing satellite measured equivalent blackbody temperatures (T_{BB}) around the storm alone and together with the changes in maximum winds during the preceding 24 hours and the current maximum wi ıds. Independent testing of these regression equations showed that the mean errors madc by the equations are lower than the errors in forecasts made by the persistence techniques.

*General Electric Space Division (MATSCO), Beltsville, Maryland 20705
**Laboratory for Atmospheric Science (GLAS) NASA/GSFC, Greenbelt, Maryland 20771

CONTENTS

ILLUSTRATIONS

PRECEDING PAGE BLANK NOT FILMED

ILLUSTRATIONS (Continued)

TABLES

PREDICTING TROPICAL CYCLONE INTENSITY USING SATELLITE MEASURED EQUIVALENT BLACKBODY TEMPERATURES OF CLOUD TOPS

1.0 INTRODUCTION

Hurricane caused damages in the United States average over $600 million per year. Damages from tropical cyclones are even much greater in many other countries on the western borders of the tropical oceans when expressed as a percentage of the gross national product. Forecasts of hurricane occurrence are, therefore, of great importance.

Observations and forecasts of hurricane wind speeds are also very important because damages caused by hurricanes vary exponentially with the maximum wind speeds. While the force of the wind varies with the square of the speed, some of the historical surveys of total storm damage suggest that the latter varies with a higher power of the wind speed, i.e.,

$$D = K V^n$$

where D is the total damage caused by the storm, K is a constant, V is the maximum wind speed and n is some number between 2 and 5 (Howard, et al., 1972). This relationship emphasizes the importance of knowing the intensity of a tropical cyclone.

In spite of the need for knowledge of tropical cyclone intensity by the hurricane forecast services, aircraft reconnaissance of tropical storms is being reduced to save money. Efforts have been increased in recent years, therefore, to use satellite data to observe and predict the intensity of tropical cyclones. Results from these efforts have been encouraging and they keep expanding as satellite data of improved quality become more readily available with each new satellite series.

Satellite measured equivalent blackbody temperatures (T_{BB}) of cloud tops in tropical cyclones should contain useful information about storm intensity and expected changes of intensity. Latent heat released when the warm moist tropical air ascends in major cumulus towers of hurricanes is the primary fuel for the storms (Dunn and Miller, 1960), and its availability is indicated by measurements of the amount and vigor of the convection within the cyclone which can be deduced from temperature measurements.

The hurricane is a prolific producer of clouds. The convective towers build far into the troposphere and sometimes penetrate the tropopause, thus producing very cold cloud tops. The high level shearing and outward spiraling winds spread the cold cirrus over a large area beyond the region of most active convection. This air subsides as it spirals away from the storm center causing the cirrus to begin dissipating as the air warms adiabatically. These spiralling subsiding effects are easily observable in satellite imagery and can be quantified through measurement of cloud top temperatures. Thus, areal distribution of the T_{BB} provide information showing the extent and strength of the convection which serve as indices of the latent heat released and indicate the extent that the clouds of the storm are organized into patterns.

The latent heat is ultimately converted to the kinetic energy which causes the extreme winds of the tropical cyclones (Riehl, 1954). For this to take place, however, there is a complex process involving among other things conversion of the heat to potential and available potential energy. Finally, the kinetic energy has to be concentrated by the flow patterns into relatively narrow bands for the storm to become truly destructive. All these processes take time and there should be a lag between changes in convective activity and changes of maximum winds in the storm.

The results of theoretical-numerical model experiments simulating development and maintenance of tropical cyclones support this reasoning and suggest that maximum vertical motion, that is, maximum convection, precedes the maximum winds by one to three days (e.g., Rosenthal, 1978; Kurihara and Tuleya, 1974). Riehl (1954) and Rosenthal (1978), have also emphasized that the convection needs to be organized by some larger scale system into a suitable pattern (e.g., spiral bands and eyewall before rapid intensification of the tropical cyclone takes place).

Dvorak and earlier investigators at the National Environmental Satellite Service have developed techniques to use satellite imagery to identify the present intensity of the tropical cyclone and to suggest future changes of the intensity (Dvorak, 1973; Hubert, et al., 1969). While these techniques have shown skill and the latest Dvorak technique is in widespread use in the tropics worldwide, it still involves considerable subjectivity especially in the forecasting of storm intensity. Dvorak (1973) utilized the degree of pattern organization to identify the current storm intensity from satellite imagery. He found that the size of the central dense overcast of cirrus and the degree to which the spiral bands of convective clouds encircled the storm center to be important factors.

Based on the heuristic reasoning just presented, results from the theoretical experiments, results of using Dvorak's technique under operational conditions, and other research, the authors developed a hypothesis to be tested by the experiments reported in this paper.

It says: (1) The T_{BB} of the tropical cyclone cloud tops provide a measure of the convection and an index of the latent heat released for eventual conversion into kinetic energy; (2) The T_{BB} areal distribution serves as an index of the organization of the storm's convective activity; and (3) The lower (higher) the mean T_{BB} of the cloud tops over a moderate sized area, the stronger (weaker) and more (less) persistent is the convection and the more likely that the maximum winds in the storm will increase (decrease) with time.

2.0 THE DATA AND THE ANALYSIS

The T_{BB} for a number of tropical cyclones were analyzed using data from the Western Atlantic for 1969 and the Western Pacific for 1970, 1973 and 1974. The T_{BB} in 1969 were measured by the MRIR sensor on NIMBUS 3 with a spatial resolution of 55km (at nadir). Those in 1970, 1973 and 1974 were measured by the THIR sensor on NIMBUS IV and V with a spatial resolution of 8km at the subpoint. These data were analyzed using the scheme illustrated in Figure 1 to get a measure of the intensity, expanse and organization of the storm. The concentric circles are 111km apart and the rings they bound are numbered outward from 1 to 12. The mean temperature was computed for each ring with the center of the diagram coinciding with the center of the storm. In addition, the mean temperature was computed for each octant of each ring (hereafter referred to as a sector) with the top of the diagram being oriented both towards the north and also along the direction of motion of the storm. To get a further measure of how well the convective towers were distributed symmetrically and concentrated about the storm center, the standard deviation of the mean sector temperatures were computed for rings 1 through 5 and for various combinations of rings. With these detailed data it is feasible to study the expanse and also the organization of the storm as well as the intensity of the convection.

3.0 T_{BB} AND STORM INTENSITY

The first tests made in this investigation were with 1969 Atlantic tropical cyclones and helped evaluate how well the temperatures demonstrated an index of convection. The mean data for the rings composited for 16 hurricanes are compared with similar data for 19 storms of less than hurricane intensity in Figure 2. For rings 1–4 (Fig. 1) the mean temperatures were 7 to 10°C lower in the hurricanes than in the weaker storms, but in rings 6–10 the hurricanes had higher temperatures. That is, the temperatures imply that hurricanes have stronger convection near the core and stronger subsidence in the environment surrounding the storm. Both the convective and subsidence areas have frequently been observed by aircraft reconnaissance and in satellite imagery (Shenk and Rodgers, 1978). The subsidence dissipates many of the clouds at distances greater than 650km from the center and thus causes the higher mean temperatures.

A similar test was made with the 1970 Western Pacific tropical cyclones. Data were composited for 3 groups of storm: those of less than typhoon intensity (15 cases), typhoons with maximum winds less than 100 knots (13 cases), and typhoons with maximum winds equal or greater than 100 knots (14 cases). The data are graphed in Figure 3, and the differences are plotted in the insert. The comparison between the weak storms and those with maximum winds greater than 99 knots is similar to that of the 1969 Atlantic storms except for ring 1 where the typhoons were warmer. This reflects the fact that many of the typhoons had large cloud free eyes and the THIR instrument used in 1970 on NIMBUS IV had sufficient resolution to measure high temperatures over smaller areas than the MRIR sensor used in 1969 on NIMBUS III. If values for ring 1 are ignored, intense storms are again colder in the inner four rings and warmer at greater radii. (Broken

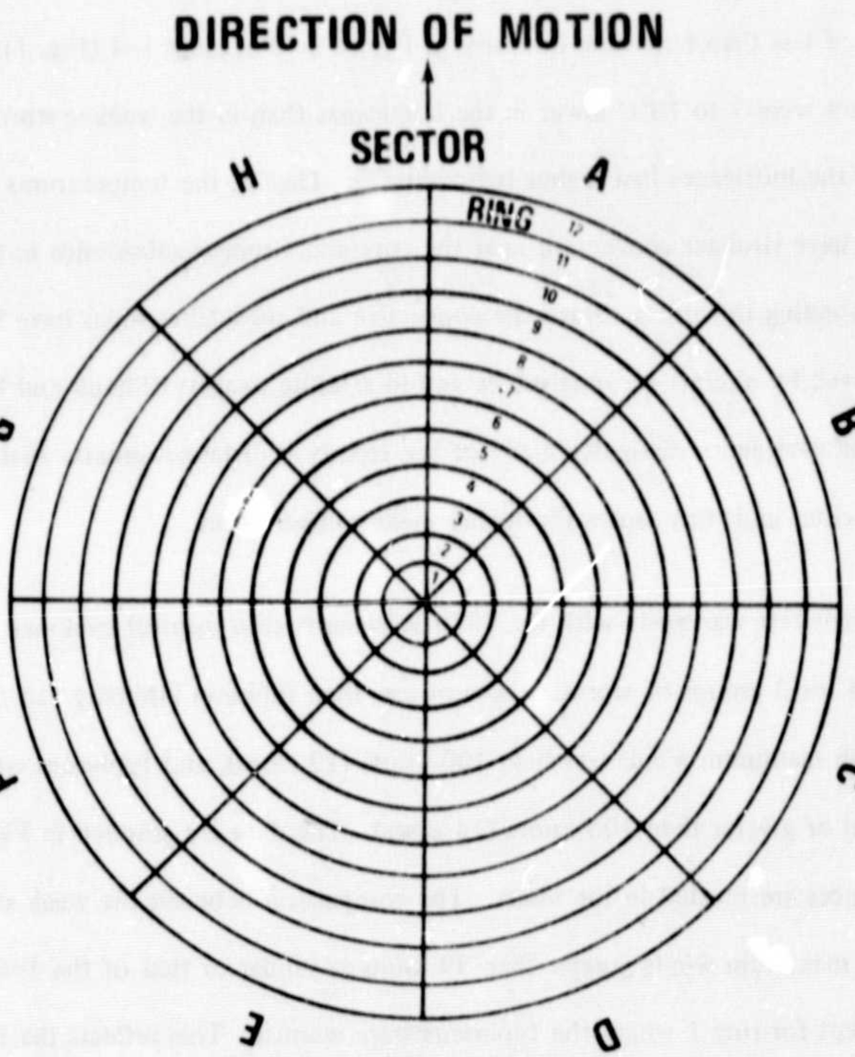

Figure 1. Grid used in analyzing the temperature data. The concentric rings are spaced 111 km apart. The center of this grid coincides with the center of the tropical cyclone.

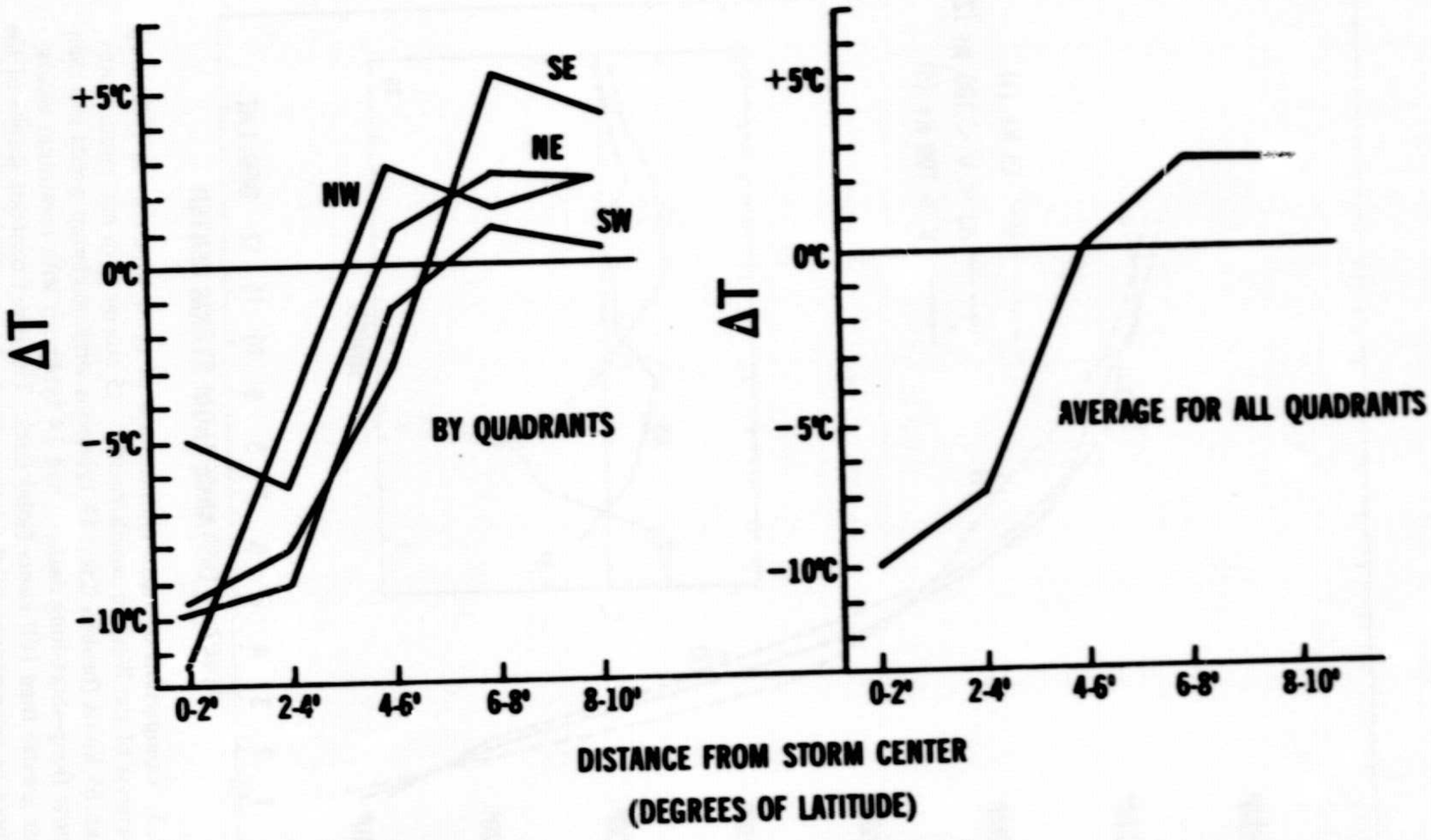

Figure 2. Comparison of mean temperatures of cloud tops around 16 hurricanes with mean temperatures from 19 storms of less than hurricane intensity. The tropical cyclones all occurred in the Western North Atlantic in 1969. The ΔT values are positive when the temperatures in the hurricanes are higher.

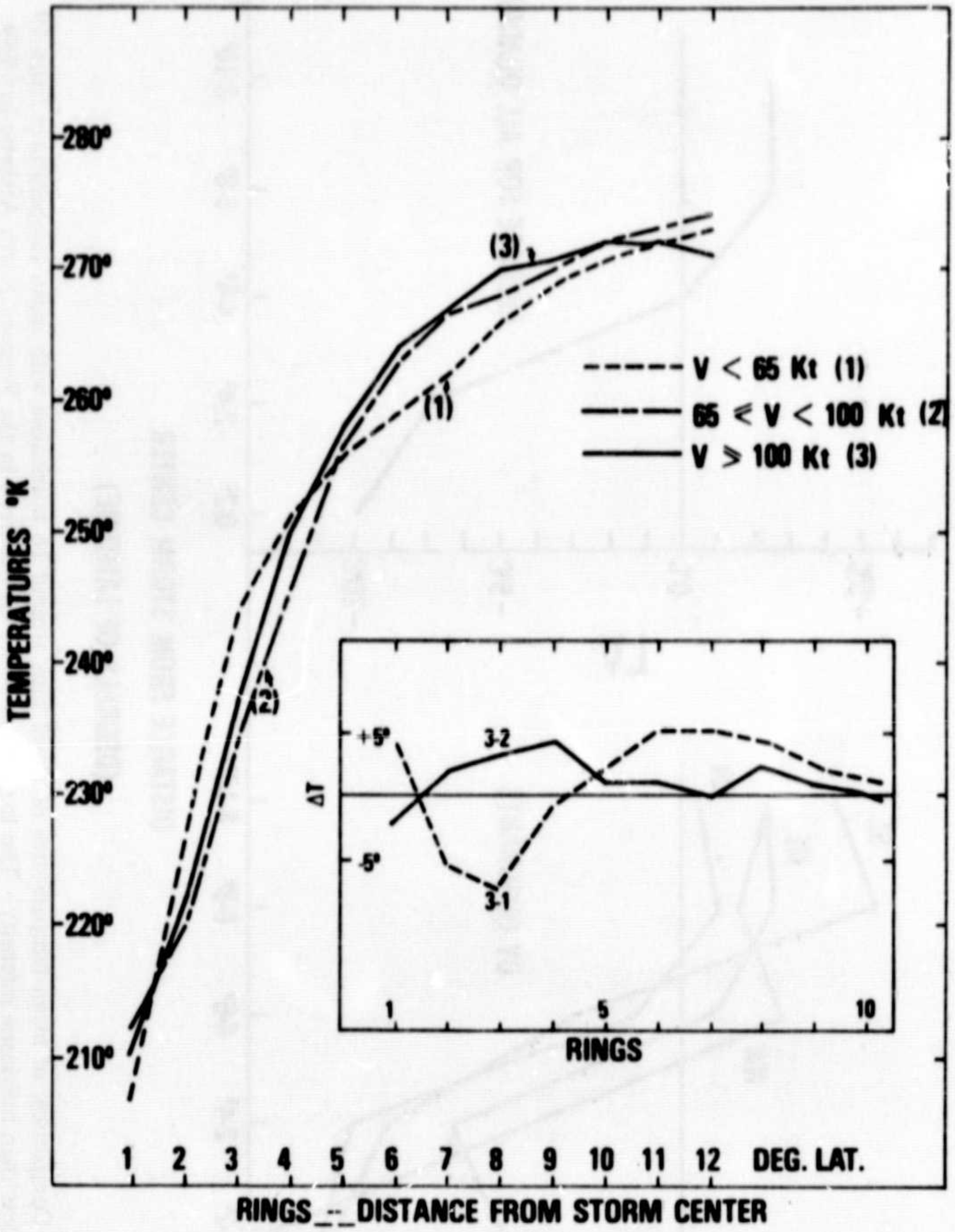

Figure 3. Comparison of mean temperatures of cloud tops around 1970 tropical cyclones of the Western North Pacific: 15 storms with maximum winds less than 65 knots (broken line); 13 typhoons with maximum winds less than 100 knots (long-short-long dashes); and 14 typhoons with maximum winds equal or greater than 100 knots (solid line). The insert contains graphs of the differences in temperatures of the latter and the two weaker categories. The rings are illustrated in Figure 1.

line labeled 3-1 in the insert.) The comparison between the typhoons of moderate intensity with the very intense typhoons (solid line, 3-2, of insert), however, gave contradictory information. An examination of the individual cases revealed that the sample of moderate intensity storms were biased toward storms that were intensifying and the more intense typhoons were biased toward mature storms that were changing slowly or were weakening. This is especially significant because it further suggests that the mean temperatures are an index of the rate of change of storm intensity.

4.0 FORECASTING STORM INTENSITY

In Figure 4 the 1970 data for storms south of 30°N are stratified according to the change of intensity during the succeeding 24 hours. The four categories used were intensifying (maximum winds increasing at least 10 knots - 12 cases), weakening (maximum winds decreasing at least 10 knots - 4 cases), little change (includes all storms which eventually reached hurricane intensity where the change during the next 24 hours was less than 10 knots - 6 cases), and a group of tropical storms which never intensified to the typhoon stage before they finally dissipated (5 cases). We can note that the storms with the greater rate of intensification are associated with the lower mean temperatures in all rings out through 9. The intensifying storms are about 18°C colder in rings 2-4 than the storms that never reached typhoon intensity, about 10°C colder in rings 1 through 8 than the weakening storms, and 5° to 10°C colder than the storms changing slowly in intensity.

Figure 5 illustrates a time-lag between the T_{BB} of the cloud tops and the changes of the maximum winds in two typhoons. The temperature scale is inverted to show the lower temperatures at the top of the diagram. To interpret the graphs one might consider the

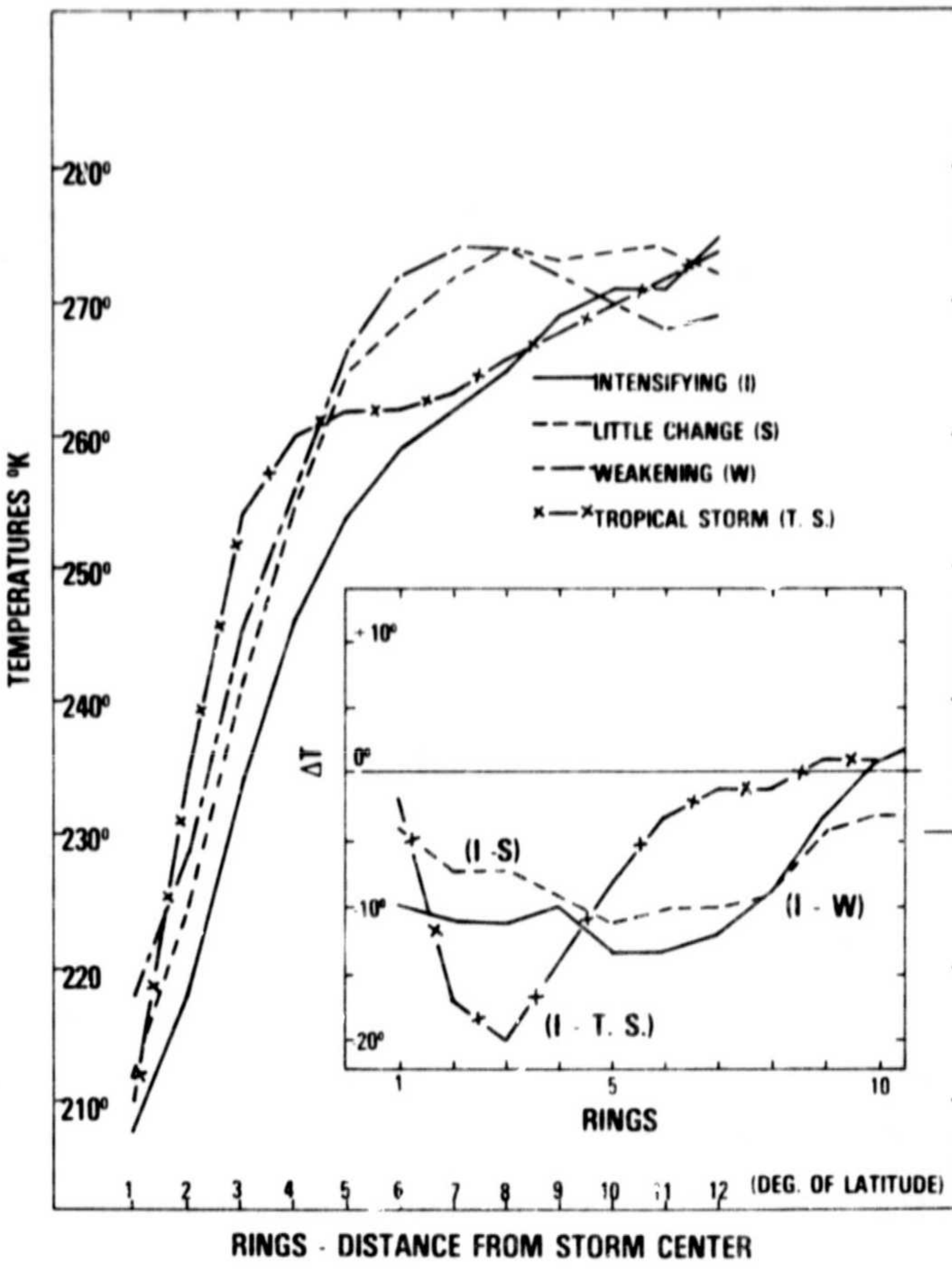

Figure 4. Same as Figure 3 except that the data are stratified according to change of intensity during next 24 hours: Maximum winds increasing 10 or more knots (I), maximum winds changing less than 10 knots (S), maximum winds decreasing 10 or more knots (W), and storms which never reached hurricane intensity (T.S.). Only storms located south of 30°N were included. The insert shows that the intensifying storms have much colder cloud tops within 8 degrees (888km) of the storm center than the others.

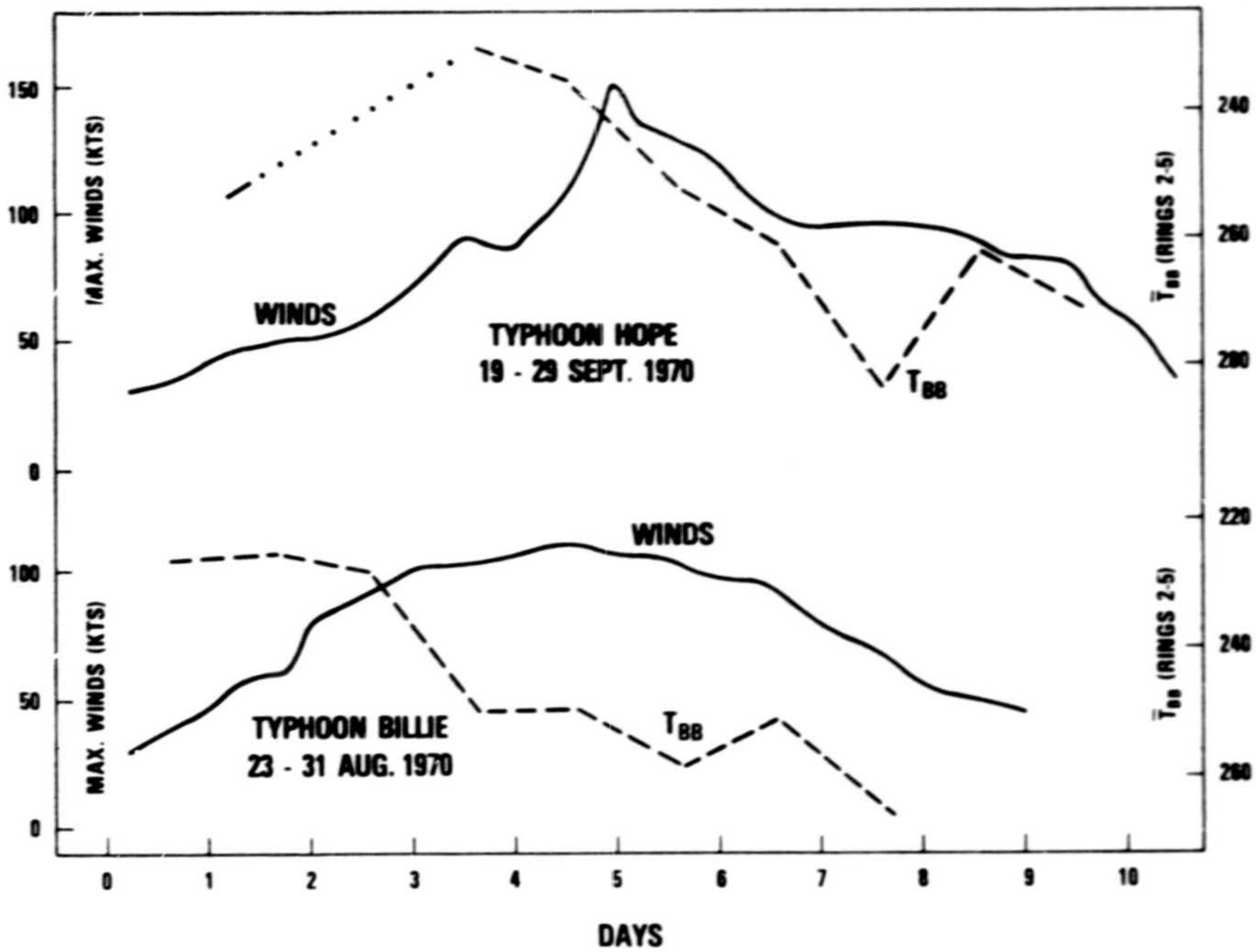

Figure 5. Temporal changes of mean equivalent blackbody temperatures (rings 2, 3 and 4 from Figure 1) and maximum winds of Typhoons Hope (Sept. 1970) and Billie (August 1970). The maximum wind changes lag the temperature changes in both cases. The temperature scale is inverted to show the lower temperatures at the top of the graph.

temperature graph as a crude index of the convective activity. Note that the minimum temperature (or maximum of the convective index) for Typhoon Billie occurred more than 2 days earlier than the maximum winds.

In the case of Typhoon Hope the wind graph maximum lags by more than one day (missing T_{BB} data make it impractical to determine the exact time of the temperature minimum). Similar data have been examined for other storms and results suggest that changes in the maximum winds lag changes in the temperatures by 24 to 36 hours. From this we can conclude that the T_{BB} contain predictive information.

Figure 6 is adapted from a simulation experiment with a theoretical model by Rosenthal (1978). The vertical velocities at 900 mb and the maximum winds are plotted against time. Here vertical velocity, rather than temperature as in Figure 5, represents convection. Note the similarity in the time lag between maximum convection and the maximum winds of the storm in the two illustrations.

Analyses of the data and heuristic reasoning suggest that the T_{BB} will vary with at least the following: rate of change of intensity of the storm, intensity of the tropical cyclone, latitude of the storm, season of the year, and mean temperatures through the surrounding troposphere. The latter means that relationships may differ for the various oceans. Because of these and other factors, the data used in preparing the composite graphs reproduced in Figures 2, 3 and 4, show considerable scatter. It was necessary therefore to consider other parameters as well as the T_{BB} when developing an objective technique for forecasting changes in tropical cyclone intensity. Even a cursory examination of the data reveals, for example, that the relationship between T_{BB} and future

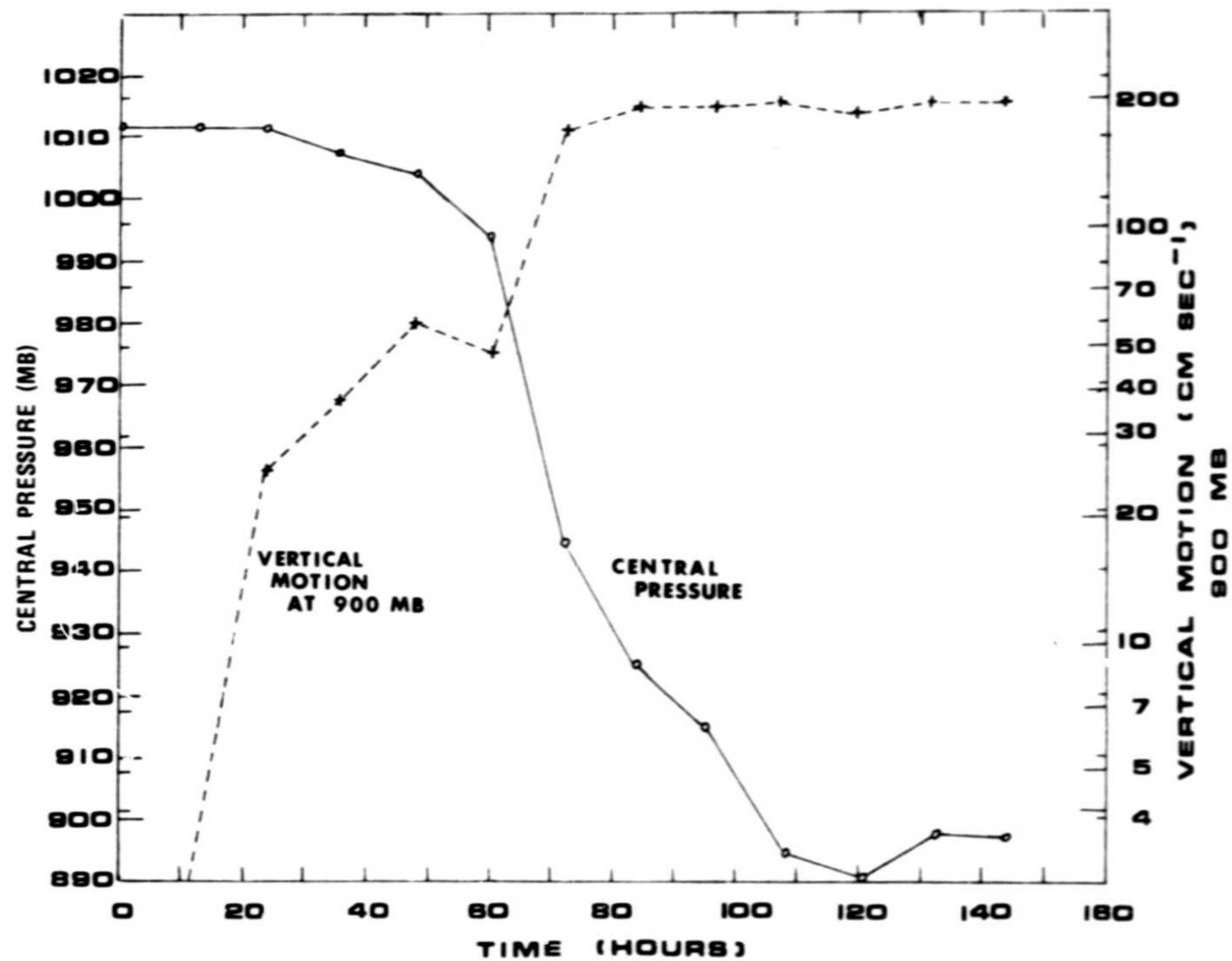

Figure 6. Comparison of Vertical Motion and Central Pressure in a Model Hurricane Showing Lag with Time (Rosenthal 1978)

storm intensity is different between storms that have been intensifying and storms that have been weakening in the preceding 12 to 24 hours. It also seems obvious that the T_{BB} are indicators of both the current and future intensities of the storm. These two effects need to be separated if a highly successful predictive scheme is to be developed. The change in maximum wind speeds during the preceding 24 hours and the current maximum wind speed helped define these effects.* A screening regression procedure selected the T_{BB} and these latter two parameters in determining the regression equations which gave the best results for forecasting maximum winds of the tropical cyclones.

Two regression equations have been developed to predict the changes in maximum winds of tropical cyclones during the next 24 hours; the first is for the weaker storms where the current maximum winds are equal or less than 65 kts, and the second is for the more intense storms.

$$V_{+24_w} = 143.75 - 0.594\overline{T}_{2,3} + 0.389\Delta V_{-24} + V_o \quad (1)$$

$$V_{+24_s} = 227.86 - 0.76\overline{T}_{1,2,3} + 0.499\Delta V_{-24} + 0.398 V_o \quad (2)$$

where

V_{+24_w} (V_{+24_s}) are predicted maximum wind speed (knots) for storms whose current maximum wind $\leqslant 65$ knots (> 65 knots).

$\overline{T}_{2,3}$ ($\overline{T}_{1,2,3}$) are T_{BB} for areas between 110 and 330km (0 and 330km) about the storm center [rings 2 and 3 (rings 1, 2, and 3)].

*The winds were extracted from the "best track" information published in the Joint Typhoon Warning Center Annual Typhoon Report for 1970, 1973, and 1974 (Reference 11, 12, and 13).

ΔV_{-24} is the change in maximum wind speed of the storm during the preceding 24 hours (knots).

V_o is the current maximum wind speed (knots) in the storm.

These equations were developed using as dependent data 58 cases from the 1970 Western Pacific tropical cyclones. Pertinent statistical information is summarized in Table 1 and show that errors of forecasts made with the above regression equations are considerably less than those of techniques using only persistence. These latter techniques have been used by forecasters for many years, and except in special situations give about as

Table 1

Mean Errors[1] of Forecasts (Knots)

Dependent Data (1970 Storms)						Independent Data (1973 and 1974 Storms)			
Equation	Vo	n	E[2]	E-NC[3]	E-P[4]	n	E[2]	E-NC[3]	E-P[4]
1	$\lesssim 65$	24	8.6	-4.0	-4.2	33	12.6	-4.2*	-0.6
2	> 65	34	9.4	-7.5	-2.6	20	16.1	-3.1	-6.9*
1 & 2	> 25	58	9.1	-6.0	-3.2	53	13.9	-3.8*	-3.0**

1. Mean errors are the means (in knots) of the absolute values of the differences between forecasted and observed maximum wind speeds.
2. E is the mean error of forecasts made by the indicated regression equation.
3. NC is the mean error of forecasts made by assuming no change in wind speed during the forecast period.
4. P is the mean error of forecasts made by assuming the wind speed would change the same amount during the next 24 hours as it did during the preceding 24 hours.

*Differences are statistically significant at the 1 percent level.
**Differences are statistically significant at the 5 percent level.

good results as any technique currently used (Gentry, 1973). They are: (1) persistence forecast assuming that no change would take place during a forecast period (NC) and (2) persistence assuming that the change during the next forecast period would be the same as the change during the preceding period (P).

Tests of Equations (1) and (2) with independent data were made using 56 storm cases from years 1973 and 1974. Statistics of the mean errors are summarized in Table 1. The errors in the forecasts made by Equations (1) and (2) are again lower than errors in forecasts made by the persistence techniques. The difference between the errors of Equation (1) and those made by forecasting no change, and the difference between errors of forecasts by Equation (2) and forecasts of persistence of change are both significant at the 1 percent level. The combination of Equations (1) and (2) make forecasts for all the storms significantly superior to either of the persistence techniques.

5.0 FORECASTS USING ONLY SATELLITE INFORMATION

The equations just evaluated used parameters other than those measured by satellites. The question may well be asked whether skill can be shown using only the satellite information and without including the change in wind speeds during the preceding 24 hours as a predictor. To answer this question, equations were developed to predict the maximum winds 24 hours in advance using only data which are measured by satellites, but assuming that the forecaster knows whether the storm has maximum winds >65 knots. This can quite reliably be determined by other techniques which use only satellite imagery (Dvorak, 1973). The mean T_{BB} was used for reasons already advanced and its variability also contributed. The degree to which the lower temperatures are evenly distributed around the storm center in the mean illustrate organization and should be a measure of the efficiency of the heat engine of the hurricane to convert heat energy into kinetic energy. This factor was taken into account somewhat by using T_{BB} averaged around a ring rather than for individual sectors. Another measure of distribution is the standard deviation of the T_{BB} in the ring. Even for intense hurricanes there will be areas of weak or no convection between cloud bands (hence relatively high temperatures). The important point is that we measure how well the cold temperatures (i.e., the active convective cells) are distributed throughout the various octants. Therefore, we used the standard deviation of the mean sector temperatures as another parameter to distinguish between intensifying and weakening tropical cyclones.

For the weaker storms ($V_o \lesssim 65$ kts), the equation developed was

$$\Delta V_{+24_w} = 167.16 - 0.682\overline{T}_{2,3} \quad (3)$$

where V_{+24_w} is the predicted change in maximum winds in the next 24 hours.

For the intense storms ($V_o > 65$ knots), the following two equations were tested.

$$V_{+24_s} = 378.51 - 1.225\overline{T}_{1,2,3} \quad (4)$$

$$V_{+24_s} = 390.72 - 1.246\overline{T}_{1,2,3} - 0.506\sigma_3 \quad (5)$$

where σ_3 is the standard deviation of the T_{BB} in the eight sectors of ring 3. The mean errors for forecasts by these equations for both dependent and independent data are given in Table 2.* The verifications listed in Table 2 for Equation (3) show it should be quite useful for identifying the weak storms that are intensifying. Results are significantly better

*Table 2 includes verifications of several equations which were tested including the information contained in Table 1. The latter was repeated to facilitate comparison of results.

Table 2

Mean Errors of Forecasts

	Dependent Data (1970 Storms)				Independent Data (1973 and 1974 Storms)			
Equation	n	E	E-NC	E-P	n	E	E-NC	E-P
Weak Tropical Cyclones ($V_0 \lesssim 65$ Knots)								
1	24	8.6	-4.0	-4.2	33	12.6	-4.2*	-0.6
3	24	9.6	-3.0	-3.2	33	12.8	-4.0*	-0.4
6	24	24.9	12.3	12.1	33	25.0	+8.2	+11.8
7	24	10.2	-2.4	-2.6	33	14.2	-2.4	1.0
Intense Tropical Cyclones ($V_0 > 65$ Knots)								
2	34	9.4	-7.5	-2.6	20	16.1	-3.1	-6.9*
2 (-11 kts)					20	11.8	-7.4*	-11.2*
4	34	11.4	-5.5	-0.6	20	18.8	2.0	5.6
5	34	10.8	-6.1	-1.2	20	18.7	1.9	5.5
6	34	21.1	4.2	9.1	20	17.4	-1.8	-5.6
7	34	12.1	-4.8	0.1	20	14.7	-4.5*	-8.3**
4 (-11 kts)					20	15.6	-3.6	-7.4*
5 (-11 kts)					20	14.9	-4.3	-8.1*
All Storms								
1 & 2	58	9.1	-6.0	-3.2	53	13.9	-3.8*	-3.0**
6	58	22.7	7.6	10.4	53	22.1	4.4	+5.2
7	58	11.4	-3.7	-0.9	53	14.4	-3.3*	-2.5

NOTES: E is mean error of forecasts made by indicated regression equation.

E-NC is mean difference in errors of forecasts made by regression equation and by assuming no change in wind speed during forecast period.

E-P is mean difference in errors of forecasts made by regression equation and by assuming the change in wind speed in the next 24 hours would be the same as the change during the previous 24 hours.

*Differences significant at 1% level.
**Differences significant at 5% level.

at the 1 percent level than forecasts of no change and superior to forecasts of persistence of change for the independent series. Equation (4) made good forecasts for the dependent data but they were inferior to those made by the persistence forecasts for the independent data series. This was also true for Equation (5), but a variation of this equation which will be discussed in Section 6 made forecasts much superior to those made by the persistence techniques even in the tests with independent data. The great value of these forecast equations is that no data other than the temperatures observed by satellite are needed except for the approximate location of the center. The center can be selected by inspection of the imagery and the grid may then be placed to compute mean temperature values. Since no knowledge is required of the previous or current intensity of the storm, except for intensity classification (over/under 65 knots), verification given in Table 2 indicates that Equations (3) and (5) could be very useful in areas where only satellite data are available.

Equations were next developed and tested which apply to all the storms, that is, they do not require classification of the storms into weak and intense categories. The accuracies (see Table 2) are good enough to suggest the equations can be very useful, especially in areas where only satellite data are readily available. These equations are:

$$V_{+24_a} = 200.51 - 2.213\sigma_{1,2} - 0.381\overline{T}_{2,3} \qquad (6)$$

$$V_{+24_a} = 146.6 - 1.569\sigma_{1,2} + 855V_o - 0.513\overline{T}_1 \qquad (7)$$

In tests on the independent data the mean of the errors is 22.1 knots for Equation (6) which uses only temperatures and their distribution, but is only 14.4 knots for Equation (7). The latter is significantly better at the 1 percent level than those of forecasts of no change and is superior to those of forecasts of persistence of change (13 percent level of significance).

Equation (7) makes the best forecasts for the intense storms of the independent series of any of the equat[illegible] presented in this paper, although forecasts for Equation (2) were slightly better for the dependent data. For the dependent series of intense storms mean error for Equation (7) was 12.1 knots which compares with errors of 16.9 and 12.0 knots respectively for forecasts of no change and persistence of change.

6.0 BIAS IN RESULTS

The results from Equation (2) without any adjustment are significantly better than those for persistence. However, examination of the errors reveals that the regression equation forecasts maximum wind speeds 11.3 knots too high in the mean for the independent cases from the 1973 and 1974 seasons. In this and latter sections a value, which will be referred to as the bias, is calculated by taking the algebraic mean of the errors. If the constant in Equation (2) were reduced by 11 knots the bias of the forecasts for independent data would be about zero and the mean error of the forecasts as defined in footnote 1 of Table 1 would be 11.8 knots which is much superior to the forecasts made by assuming either no change or persistence of change. In fact, it is probably better than the forecasters are currently doing.* The magnitude of the mean error is not especially sensitive to the particular value used in reducing the constant term. For example, the mean error varies from 12.7 to 11.6 knots if the constant is reduced by various values ranging from

*It is considerably smaller than 13.5 knots which is the average error the forecasters had for the 1973 and 1974 seasons. It has not been practical, however, to make comparison with what the forecasters did in the particular 20 cases used in this study.

8 to 17 knots. The critical question is then, why does the equation forecast consistently too high values? Did the sensor calibration change or was there really that much change in the relationship between mean temperatures and maximum wind speeds from 1970 to the 1973-1974 seasons?

Since two satellites were used in collecting the dependent and independent data, checks were made to determine if calibration of the sensors varied. The T_{BB} near both the cold and warm limits of the scale were compared to determine if there was variability in the observed values between the sensors of NIMBUS IV and V. The mean T_{BB} of the coldest sectors of the typhoon served as values for lower limit temperatures and the clear area sea surface temperature values functioned as the upper limit. The differences between the values of the two satellites were slight ($<2°C$) in both magnitude and range. The data from one satellite were therefore considered to be compatible to those of the other.

In earlier paragraphs it was explained that the relationship between storm intensity and mean cloud top temperatures probably varied with latitude, season, sea surface temperatures and height of the tropopause, as well as the parameters evaluated. Table 3 compares the distribution of the dependent and independent cases both temporally and spatially. It is obvious that there are large differences. For example in the dependent cases for intense storms 88 percent of the cases occur in the months of August through October. By contrast for the independent data only 45 percent of the cases come during those months. For the weak storms only 12.5 percent of the cases come during May, June and July, but for the independent data 51.5 percent of the cases occur during those months.

Table 3

Distribution of Storms by Months

Month	Weak Storms ($V_o \leq 65$ Kt)				Intense Storms ($V_o > 65$ Kt)			
	Dependent Data		Independent Data		Dependent Data		Independent Data	
	n	Mean Error of Forecasts	n	Mean Error of Forecasts	n	Mean Error of Forecasts	n	Mean Error of Forecasts
May, June, July	3	5.2	17	0.7	2	1.2	7	10.7
August	6	0.2	2	-7.8	14	-2.0	3	5.9
September	5	3.2	7	-14.6	7	2.4	3	5.7
October	3	-20.4	6	0.2	9	3.3	3	13.0
November	7	+4.0	1	10.7	2	-10.7	4	19.5
All Cases	24	0.0	33	-3.0	34	0.0	20	11.3

Distribution of Storms by Latitude

Latitude	Weak Storms ($V_o \lesssim 65$ Kt)				Intense Storms ($V_o > 65$ Kt)			
	Dependent Data		Independent Data		Dependent Data		Independent Data	
	n	Mean Error of Forecasts	n	Mean Error of Forecasts	n	Mean Error of Forecasts	n	Mean Error of Forecasts
$\lesssim 10°$					2	1.0		
$10 < LL \lesssim 20°$	19	-0.9	24	-0.9	11	-4.2	8	11.8
$20° < LL \lesssim 30°$	4	2.3	6	-6.6	12	4.3	10	10.1
$> 30°$	1	7.9	3	-11.8	9	-0.7	2	15.8
Total	24	0.0	33	-3.0	34	0.0	20	11.3

Distribution of Storms by Areas

	Weak Storms ($V_o \lesssim 65$ Kt)				Intense Storms ($V_o > 65$ Kt)			
	Dependent Data		Independent Data		Dependent Data		Independent Data	
	n	Mean Error of Forecasts	n	Mean Error of Forecasts	n	Mean Error of Forecasts	n	Mean Error of Forecasts
Latitude > 15°, Longitude > 125°	7	-1.0	13	-12.4	20	-0.4	14	3.0
Longitude < 121°	10	-0.4	14	0.8	6	5.9	3	19.3
Latitude < 28°, Longitude > 123°	11	-0.5	15	0.1	17	-1.6	12	12.6

Mean Errors (Mean Bias)

Weak Storms ($V_o \lesssim 65$ Kt)							Intense Storms ($V_o > 65$ Kt)							
Dependent			Independent				Dependent				Independent			
Reg.	No. Ch	Pers. of Ch	n	Reg.	No Ch	Pers. of Ch	n	Reg.	No Ch	Pers. of Ch	n	Reg.	No Ch	Pers. of Ch
0.0	5.1	1.5	33	-3.0	-13.1	0.5	34	0.0	-1.4	10.6	20	11.3	0.8	16.7

Reg. is the appropriate regression Equation.
No. Ch is no change.
Pers. of Ch is Persistance of Change.

The distribution by latitude is more comparable, nevertheless there are differences. For example with the intense storms, 2 from the dependent series occurred at latitudes considerably less than 10 degrees and 9 were at latitudes greater than 30 degrees. From the independent sample none were south of 10 degrees and only 2 were north of 30 degrees. These differences between the samples motivated investigation of whether latitudinal or seasonal differences in the relationship between mean temperature and maximum winds could account for the bias in the forecast errors for the 1973 and 1974 seasons.

There are certainly differences. For the weak storms in November the bias of the forecasts is +4 knots for the dependent series and +10.7 knots for the independent series. Likewise in October for the intense storms the bias for the dependent series is +3.3 knots and 13.0 knots for the independent series. For the latitude belt between 20 and 30 degrees north latitude for the intense storms the bias for the dependent cases is 4.3 knots and 10.1 knots for the independent cases. These suggest that the bias in the distribution might account for part of the bias in the forecast errors. There are, however, a lot of inconsistencies between the dependent and independent data. For example the mean error for the intense storms is −10.7 knots in November for the dependent and +19.5 knots for the independent cases. Likewise +2.3 knots in the latitude belt of 20–30 degrees for the dependent cases of the weak storms and −6.6 knots for the independent series. Even the case of 4.3 knots versus 10.1 knots quoted earlier for the belt of 20–30 degrees north latitude of the intense storms is inconsistent. That is, for the dependent series the bias is 4.3 knots greater than the bias for all the storms in that series, while the +10.1 knots for the independent series is 1.2 knots less than the bias for all the storms. Because of these inconsistencies, further analyses were made. Regression equations were developed for both the dependent and independent series relating the errors of the forecasts made by Equation (1) or (2) to the errors made by forecasts of no change and forecasts of persistence of changes. These regression equations accounted for 64 and 69 percent of the variance in the errors of the forecasts made by Equations (1) and (2) for the dependent and independent series respectively. That is, the errors in forecasts made by Equations (1) and (2) are highly correlated with the rate at which storms change intensity or acceleration in the rate of change of intensity during forecast periods. Using these relationships, further analyses were made by month and area of the bias in errors. In some cases where the mean error had been positive, this analysis suggested the bias of the error should be negative or vice versa.

In summary, the principal conclusion is that with the number of cases available it is very difficult to assign any large portion of the error to latitudinal or seasonal variations. In most cases there were enough inconsistencies between indications from the dependent and independent series as to make conclusions doubtful. The only cases in which there is sufficient consistency are:

Weak storms:
1. May, June and July forecasts are too high by a small amount. (−1)
2. November forecasts are too high. (−2)
3. Area > 15 degrees north latitude and > 125 degrees east longitude forecast values are too low. (+4)

Intense storms:
1. October forecasts are too high. (−2)
2. South China Sea storm forecasts are too high. (−2)

Numbers in parentheses by each case are best estimates of the correction that should be applied to forecasts made by Equations (1) and (2). It should be emphasized that these corrections are not supported by adequate data and might be quite different for another sample. They should be used, if at all, with great caution. It is obvious, however, from the magnitude of the indicated corrections and the lack of indications for many of the cases, that one cannot account for the large bias in the error of the independent cases of the intense storms by seasonal or locational bias in the data sample.

Another explanation appears more likely for the bias. Atkinson and Holliday (1977) discussing techniques used at Guam's Joint Typhoon Warning Center (JTWC) to convert observed central pressures to estimated maximum winds for tropical cyclones wrote: "There was considerable uncertainty involved in the existing equations and a general belief among JTWC forecasters that they overestimated the maximum winds. Therefore, in 1973 a new pressure–wind relationship developed by Fujita, <u>et al.</u>, (1971) was adopted for operational use. While the Fujita relationship appeared to give more realistic wind values, a large-scale data collection effort (described in the next section) was initiated to obtain sufficient information to verify or refine the existing relationships."

Captain Holliday was a forecaster in JTWC 1970–1975. Col. Atkinson was Director of the JTWC in 1973 and 1974. In a personal communication Captain Holliday reports there was a definite change in philosophy among the JTWC forecasters by early 1974 when they were preparing the "best track" information for the 1973 season. He says by then the information reported by Atkinson and Holliday (1977) was largely available and was used in converting 700 mb heights and sea level pressures measured by reconnaissance aircraft to maximum winds at a lower value for the "best track" presentation for the 1973 and 1974 seasons than they did for the 1970 season. He could not estimate the magnitude effected by the change but thought that applying the Takahashi (1952) and Atkinson and Holliday (1977) equations to representative data might provide a realistic estimate.

Takahashi's later work suggested that the constant in his equation should be changed when the storms were at higher latitudes. The three equations below are from Atkinson and Holliday's paper (1977). Equation (8) was developed by them, Equation (9) is from Takahashi's paper (1952), and Equation (10) is Takahashi's equation for higher latitudes. Table 4 compares the maximum winds calculated from a range of minimum central pressures by the three equations.

Table 4

Relations Between Minimum Central Pressure and Maximum Winds in Tropical Cyclones

P_c	V_{m_1}	V_{m_2}	V_{m_3}
1000	30	42	36
990	46	60	51
980	60	73	63
970	72	85	73
960	83	95	81
950	94	104	89
940	103	112	96
930	113	120	103
920	122	127	109
910	130	134	115
900	138	141	121
890	146	1[illegible]7	

$$V_{m_1} = 6.7(1010 - P_c)^{0.644} \quad (8)$$

$$V_{m_2} = 13.4(1010 - P_c)^{0.5} \quad (9)$$

$$V_{m_3} = 11.5(1010 - P_c)^{0.5} \quad (10)$$

P_c is the central pressure of the storm in millibars, and V_m is the calculated maximum wind speed in the storm at the time P_c was measured.

In the independent sample of 20 intense storms from the 1973–1974 seasons, 2 of the storms were at latitudes greater than 30 degrees. Assuming Takahashi's Equation (10) for higher latitudes applies to these 2 storms and Equation (9) applies to the other 18 storms, then the differences between results from Equation (8) and the combination of Equations (9) and (10) in calculating maximum wind speeds for intense storms are as follows:

Table 5

Variation of Maximum Winds Related to Central Pressure

P_c	Difference in Maximum Winds (Knots)
980	12
970	12
960	11
950	9
940	7
930	5

The mean of the maximum winds for the independent data cases was 88 knots. From Equation (8) this means a central pressure of 955 knots. Table 5 suggests a difference between the maximum winds for 1970 and those of 1973, 1974 of 10 knots. At this late date it is not practical to reconstruct all of the work the forecasters did in preparing the "best track" data for 1970, 1973 and 1974. The above results however suggest that changes in procedures at the JTWC may account for much of the bias observed.

If the change in procedures can account for the bias observed in the forecasts made by Equation (2) a further check would be provided by comparing its constant term with the one in a regression equation developed using the 1973, 1974 sample as dependent data. An equation of the same form as Equation (2) developed using 1973 and 1974 data as dependent data is:

$$V_{+24_I} = 243.91 - 0.885\overline{T}_{1,2,3} + 0.385\Delta V_{-24} + 0.424 V_o \qquad (11)$$

At first inspection the constant here appears to be considerably larger, rather than smaller, than the one in Equation (2), but the other terms conceal part of the constant. For example, Equations (2) and (11) can be expressed respectively,

$$V_{+24_S} = 227.86 - 0.76[210 + (T_{1,2,3} - 210)] + 0.499\Delta V_{-24} + 0.398[65 + (V_o - 65)] \qquad (12)$$

$$V_{+24_I} = 243.91 - 0.885[210 + (T_{1,2,3} - 210)] + 385\Delta V_{-24} + 0.424[65 + (V_o - 65)] \qquad (13)$$

If the equations are simplified and if (13) is subtracted from (12),

$$V_{+24_S} - V_{+24_I} = 8.5 + 0.125(\overline{T}_{1,2,3} - 210) + 0.114\Delta V_{-24} - 0.026(V_o - 65)$$

If this is solved for representative values, e.g., $\overline{T}_{1,2,3} = 230°K$ and $V_o = 90$ knots, then

$$V_{+24_S} - V_{+24_I} = 10.9 \text{ knots.}$$

The bias for Equation (2) when tested on independent data was 11.3 knots.

Forecasts made by Equation (2) with the constant reduced by 11.3 and those made with Equation (11) have a correlation of 0.9899 and the bias in the forecasts is -0.015. The mean difference in the absolute value of the errors is 1.6 knots and the standard deviation of these absolute values is 2.1 knots.

Results of the testing are quite convincing that both the 1970 and 1973–74 series show a real relationship between the T_{BB} around a typhoon and the change in maximum winds during the next 24 hours. Furthermore, the relationships for the 2 periods agree quite closely except for the constant term. Further evidence that the change in procedures at JTWC account for much of this bias is as follows:

Checks were next made with Equation (4) which did not use the change in maximum winds during the preceding 24 hours as a predictor. Another equation, (14), was derived in the same format using 1973 and 1974 data as dependent.

$$V_{+24_S} = 378.51 - 1.225\overline{T}_{1,2,3} \qquad (4)$$

$$V_{+24_I} = 398.9 - 1.375\overline{T}_{1,2,3} \qquad (14)$$

If (4) and (14) are treated as in the preceding paragraphs and subtracted,

$$V_{+24_S} - V_{+24} = 11.11 + 0.15(\overline{T}_{1,2,3} - 210) \qquad (16)$$

When $\overline{T}_{1,2,3}$ = 230°K is substituted, the result is 14.1 knots. The bias of forecasts made for 1973–74 data with Equation (4) was 13.6 knots.

Likewise, the more complete Equation (5) was tested by comparing with a similar equation, (17), developed using 1973–1974 data as dependent.

$$V_{+24_S} = 390.72 - 1.246\overline{T}_{1,2,3} - 506\sigma_3 \qquad (5)$$

$$V_{+24_I} = 395.3 - 1.333\overline{T}_{1,2,3} - 0.404\sigma_3 \qquad (17)$$

When the equations are subtracted,

$$V_{+24_S} - V_{+24_I} = 13.078 + 0.087(\overline{T}_{1,2,3} - 210) - 102(\sigma_3 - 6)$$

which for $\overline{T}_{1,2,3} = 230°K$ and $\sigma_3 = 10$, becomes 14.4 knots. The bias of forecasts made for 1973-74 data with Equation (5) was 13.7 knots.

Mean errors for forecasts made with Equations (4) and (5) for the 1973-74 series when constants in equations were reduced by 11 knots were 15.6 and 14.9 knots respectively. Reference to Table 2 shows that both of these mean errors are considered smaller than those of forecasts made by assuming either no change or persistence of change and they are significantly better at the one percent level than the errors made by forecasts assuming persistence of change.

Simulated operational tests were also made of the regression equations. The wind speed data used thus far in developing and checking the regression equations were all taken from the "best track" information prepared at JTWC. Wind data for the independent series have been published in the Annual Reports prepared at the JTWC (U.S. Fleet Weather Central/JTWC, 1970, 1973 and 1974) not only in the "best track" reports but also as observed on reconnaissance flights and as used in the typhoon advisories prepared at the time. Times of these latter reports did not coincide exactly with time of satellite temperature data. The advisory prepared within a few hours (less than 6 hours in all cases) after a satellite pass contained an estimate of the maximum wind based on information collected at approximately the same time as the satellite overflight. The data for

V_0, ΔV_{-24} and ΔV_{+24}, therefore, were taken from the advisories and used to test Equations (1) and (7) for the weak storms and Equations (2) and (7) for the storms with $V_0 > 65$ knots. In all cases the differences between the mean errors of the regression equations and corresponding mean errors of persistence forecasts were greater than those listed in Table 2. That is using simulated operational data caused greater increases in the errors of persistence forecasts than for the regressions equations.

The forecasts made at JTWC for the same days as the forecasts made by the regression equations for the independent data series are not readily compared with the latter. Their starting times coincide with the advisory times which usually differ from the times of the satellite passes. Furthermore, the corresponding official forecast was not always included in the annual reports of JTWC. To the extent information was available, however, we verified that the mean error of the official JTWC forecasts for the storms having $V_0 > 65$ knots for the days used in the experimental forecasts reported in this paper were much larger than the mean errors of the JTWC forecasts for the entire 1973 and 1974 seasons. This helps explain why the mean errors of all the forecasts (by regression equation, persistence and no change) were larger for the independent data than they were for the dependent series. That is, the independent series was biased toward situations which were difficult to forecast by procedures normally used.

7.0 CONCLUSIONS

Evidence presented in preceding paragraphs strongly suggest that the relationship between satellite measured T_{BB} around tropical cyclones and changes in maximum winds of the storms during the next 24 hours is real and is sufficiently strong to be a useful forecast tool. T_{BB} can be used to obtain reasonably good results when used alone, and can greatly enhance the value of other indications of intensity changes when other significant data are available for use by the forecasters.

More work, however, needs to be done to evaluate at least the constant in the equations. Besides the variation between years for the Western North Pacific data which is probably accounted for at least in part by a change in procedures of the forecasters, there may well be a variation between oceans. The data presented in Table 3 suggest that there is at least a small variation by months and by geographical location. It certainly would seem logical that there would be some variation, for the T_{BB} of the cloud tops are probably not only a function of the strength of the convection, but also a function of the sea temperature, the lapse rate in the troposphere, and the height of the tropopause. All of these vary in the mean with the season, and with the geographical area. Certainly the proximity of land could also have some influence on the relationship.

The results presented herein are sufficiently promising that it would seem desirable to further investigate the relationship between satellite data and storm intensity with more cases which would permit further stratification of the data. In particular, data need to be examined from the principal tropical cyclone regions of the other oceans in the world to see if there is any great variability between regions. Some data collected from the Western Atlantic and Eastern Pacific suggest that the T_{BB} is a useful forecast parameter, but too few cases from those regions have been examined to state stronger conclusions.

REFERENCES

Atkinson, Gary D. and Charles R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the Western North Pacific, Mon. Wea. Rev., 105, 421–27.

Dvorak, Vernon R., 1973: A technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures. NOAA Technical Memorandum NESS45, Department of Commerce, 19 pp.

Dunn, Gordon E. and Banner I. Miller, 1960: Atlantic Hurricanes, Louisiana State University Press, pp. 123 ff.

Fujita, T., 1971: Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity, SMRP Research Paper 91, University of Chicago, 41 pp.

Gentry, R. Cecil, 1973: Forecasting development and intensity of tropical cyclones, Proceedings Regional Tropical Cyclone Seminar, Brisbane, May 1973, World Meteorological Organization, pp. 159–171.

Howard, Ronald A., James E. Matheson, and D. Warner North, 1972: The decision to seed hurricanes, Science, 176, 1191–1201.

Hubert, L. F., A. Timchalk, and S. Fritz, 1969: Estimating maximum wind speed of tropical storms from high resolution infrared data, ESSA Technical Report NESC50, U.S. Department of Commerce, 33 pp.

Kurihara, Y. and R. E. Tuleya, 1974: Structure of a tropical cyclone developed in a three-dimensional numerical simulation model, J. Atmos. Sci., 31, 893-919.

Riehl, Herbert, 1954: Tropical Meteorology, McGraw-Hill Book Company, Inc., New York, 392 pp.

Rosenthal, Stanley L., 1978: Numerical simulation of tropical cyclone development with latent heat release by the resolvable scales, I: Model description and preliminary results, J. of Atmos. Sci., 35, 258-271.

Shenk, William E. and Edward B. Rodgers, 1978: NIMBUS 3/ATS 3 observations of the evolution of Hurricane Camille, J. of Appl. Meteor., 17, 458-76.

Takahashi, K., 1952: Techniques of the Typhoon Forecast, Geophys. Mag., Tokyo, 241-8.

U.S. Fleet Weather Central/Joint Typhoon Warning Center, 1970: Annual Typhoon Report, U.S. Navy Report, Guam, 220 pp.

U.S. Fleet Weather Central/Joint Typhoon Warning Center, 1973: Annual Typhoon Report, U.S. Navy Report, Guam, 94 pp.

U.S. Fleet Weather Central/Joint Typhoon Warning Center, 1974: Annual Typhoon Report, U.S. Navy Report, Guam, 113 pp.

FIGURE CAPTIONS

Figure 1. Grid used in analyzing the temperature data. The concentric rings are spaced 111 km apart. The center of this grid coincides with the center of the tropical cyclone.

Figure 2. Comparison of mean temperatures of cloud tops around 16 hurricanes with mean temperatures from 19 storms of less than hurricane intensity. The tropical cyclones all occurred in the Western North Atlantic in 1969. The ΔT values are positive when the temperatures in the hurricanes are higher.

Figure 3. Comparison of mean temperatures of cloud tops around 1970 tropical cyclones of the Western North Pacific: 15 storms with maximum winds less than 65 knots (broken line); 13 typhoons with maximum winds less than 100 knots (long-short-long dashes); and 14 typhoons with maximum winds equal or greater than 100 knots (solid line). The insert contains graphs of the differences in temperatures of the latter and the two weaker categories. The rings are illustrated in Figure 1.

Figure 4. Same as Figure 3 except that the data are stratified according to change of intensity during next 24 hours: Maximum winds increasing 10 or more knots (I), maximum winds changing less than 10 knots (S), maximum winds decreasing 10 or more knots (W), and storms which never reached hurricane intensity (T.S.). Only storms located south of 30°N were included. The insert shows that the intensifying storms have much colder cloud tops within 8 degrees (888 km) of the storm center than the others.

FIGURE CAPTIONS (Continued)

Figure 5. Temporal changes of mean equivalent blackbody temperatures (rings 2, 3 and 4 from Figure 1) and maximum winds of Typhoons Hope (Sept. 1970) and Billie (August 1970). The maximum wind changes lag the temperature changes in both cases. The temperature scale is inverted to show the lower temperatures at the top of the graph.

Figure 6. Comparison of Vertical Motion and Central Pressure in a Model Hurricane Showing Lag with Time (Rosenthal 1978)

TABLE CAPTIONS