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

R. CECIL GENTRY[1]

Department of Physics and Astronomy, Clemson University, Clemson SC 29631

EDWARD RODGERS

Laboratory for Atmospheric Science (GLAS), NASA/Goddard Space Flight Center, Greenbelt, MD 20771

JOSEPH STERANKA

General Electric Space Division (MATSCO), Beltsville, MD 20705

WILLIAM E. SHENK

Laboratory for Atmospheric Science (GLAS), NASA/Goddard Space Flight Center, Greenbelt, MD 20771

(Manuscript received 14 December 1978, in final form 17 December 1979)

ABSTRACT

A relationship between maximum winds and satellite-measured equivalent blackbody temperatures near tropical cyclones is investigated with data from both the Atlantic and western North Pacific areas. This investigation revealed not only a significant correlation between satellite-derived equivalent blackbody temperatures and maximum winds but also a strong lag relationship between these temperatures and maximum winds. From this latter relationship a regression technique was developed to forecast 24 h changes of the maximum winds for weak (maximum winds $\leq$ 65 kt) and strong (maximum winds $>$ 65 kt) tropical cyclones by utilizing the equivalent blackbody temperatures around the storm alone, and together with changes in maximum winds during the preceding 24 h and the current maximum winds. Testing of these equations with independent data showed that the mean errors of forecasts made by the equations are lower than the errors in forecasts made by persistence techniques.

1. Introduction

Hurricane caused damages in the United States average over $600 million per year (Gentry, 1966).[2] Damages from tropical cyclones are even much greater in many other countries on the western borders of tropical cyclone basins when expressed as a percentage of the gross national product. Forecasts of where and when a hurricane will strike are obviously of great importance.

Observations and forecasts of the maximum winds in hurricanes 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 damage varies with a higher power of the wind speed, i.e.,

$$D = KV^n, \tag{1}$$

where D (total damage) is the total damage caused by the storm, K a constant, V the maximum wind speed, and n some number between 2 and 5 (Howard *et al.*, 1972). This relationship emphasizes the importance of knowing and predicting the intensity of a tropical cyclone. Furthermore, contrary to the improvements made in predicting tropical cyclone movement, relatively little progress has been made in the last 20 years in developing improved objective techniques for forecasting maximum winds of these storms. Except in special situations, forecasters still rely very heavily on persistence and climatological techniques when forecasting tropical cyclone intensity. As a result, operational skill in forecasting maximum wind speeds in hurricanes remains low.

In spite of the need for knowledge of tropical cyclone intensity by the hurricane forecast services, aircraft reconnaissance of these storms on the average is being reduced for economic reasons. Efforts

---

[1] Formerly associated with General Electric Space Division (MATSCO), Beltsville, MD 20771.

[2] Updated using records at the National Hurricane Center, Miami, Florida.

0027-0644/80/040445-11$06.75

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 very encouraging and they keep improving as satellite data of better quality become more readily available with each new satellite series.

While satellite and other platforms usually provide sufficient information to identify the current intensity of tropical cyclones, relatively few satellite data (visible, infrared or passive microwave) have been utilized in predicting changes in intensity, and then primarily in a qualitative sense. Satellite measured equivalent blackbody temperatures (T_{BB}) of cloud tops in tropical cyclones are believed to 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 the amount and vigor of the convection within the cyclone. This can be deduced from satellite T_{BB} measurements.

The hurricane is a prolific producer of clouds. The convective towers build far into the troposphere and sometimes penetrate the lower stratosphere, 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 its spirals away from the storm center causing the cirrus to begin dissipating as the air warms adiabatically. These effects are easily observable in satellite imagery and can be quantified through measurement of cloud-top temperatures. Thus, areal distribution of T_{BB} provides information on the extent and strength of the convection which serve as indices of the latent heat released and indicate the extent to which 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, complex processes are involved including, among other things, conversion of the heat to potential and available energy. Finally, the kinetic energy has to be concentrated by the flow patterns usually 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 the reasoning and suggest that maximum vertical motion, i.e., maximum convection precedes the highest winds by 1–3 days (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 eye-wall) 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, 1975; 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 (1975) 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. Others who recently have studied the relationship between satellite measurements of clouds and tropical cyclone intensity, convection or rainfall include Arnold (1977) and Griffith *et al.* (1978).

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 have developed a hypothesis 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. The data and the analysis

The infrared (11.5 μm, window channel) T_{BB} for a number of tropical cyclones over open ocean areas were analyzed using data from the western Atlantic for 1969 and the western Pacific for 1970, 1973 and 1974. The 1969 T_{BB} were measured by the Medium Resolution Infrared Radiometer (MRIR) sensor on Nimbus 3 with a spatial resolution of 55 km at nadir. Those in 1970, 1973 and 1974 were measured by the Temperature Humidity Infrared Radiometer (THIR) sensor on Nimbus 4 and 5 with a spatial resolution of 8 km at the subpoint. Further details of the Nimbus 3, 4 and 5 satellites and their instrumentations are provided in the Nimbus 3, 4 and 5 *User's Guides* (Nimbus Project 1969, 1970, 1972). These data were analyzed using the scheme illustrated

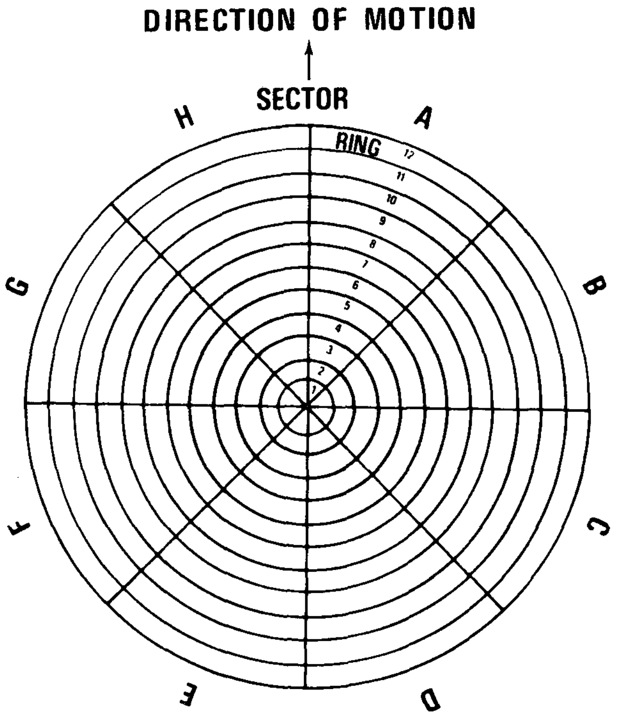

FIG. 1. Grid used in analyzing the temperature data. The concentric rings are spaced 111 km apart. The center of this grid coincides with the center of the tropical cyclone.

in Fig. 1 in order to obtain a measure of the intensity, expanse and organization of the storm. The concentric circles are 111 km apart and the rings they bound are numbered outward from 1 to 12. The mean T_{BB} was computed for each ring with the center of the diagram coinciding with the center of the storm. In addition, the mean T_{BB} was calculated for each octant of each ring (hereafter referred to as a sector) with the top of the diagram being oriented both toward the north and also along the direction of motion of the storm.[3] To get a further measure of how well the convective towers were distributed symmetrically and concentrated about the storm center, the standard deviations of the mean sector temperatures were computed for rings 1–5 and for various combinations of rings. With these data it is feasible to study the expanse and also the organization of the storm as well as the intensity of the convection.

The wind data for each Atlantic storm were obtained from the best track records maintained at the National Hurricane Center. The wind data for each Pacific storm were obtained from the best track and warning information compiled by the Joint Typhoon Warning Center, Guam (U.S. Fleet Weather Central, Joint Typhoon Warning Center, 1970, 1973, 1974). A linear interpolation of wind was made when satellite observation time occurred between the best track data times.

3. T_{BB} and storm intensity

The first tests made in this investigation were with 1969 Atlantic tropical cyclones. This investigation determined how well the cloud top T_{BB} 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 (three of the tropical cyclones were still at depression stage) in Fig. 2. For rings 1–4 (Fig. 1) the mean T_{BB} were 7–10°C lower in the hurricanes than in the weaker storms, but in rings

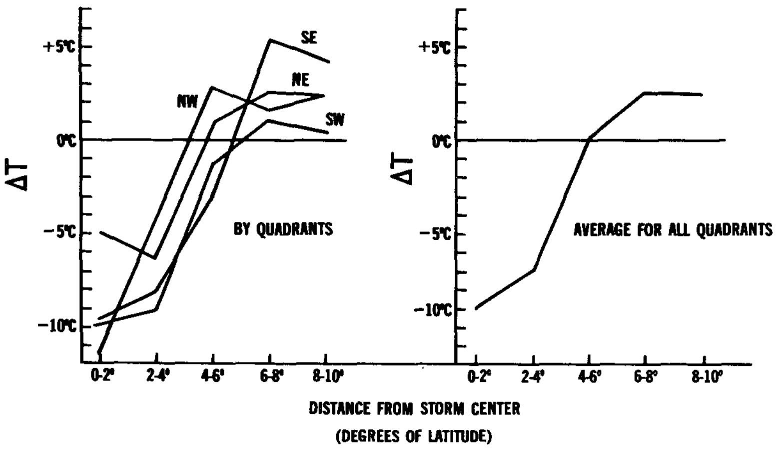

FIG. 2. Comparison of mean temperatures of cloud tops around 16 hurricanes with mean temperatures from 19 storms of less than hurricane intensity, all in 1969. The tropical cyclones all occurred in the western North Atlantic in 1969. The ΔT values are positive when the temperatures in the hurricanes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

---

[3] Since all results reported in this paper used the entire ring of data, storm orientation is of no concern.

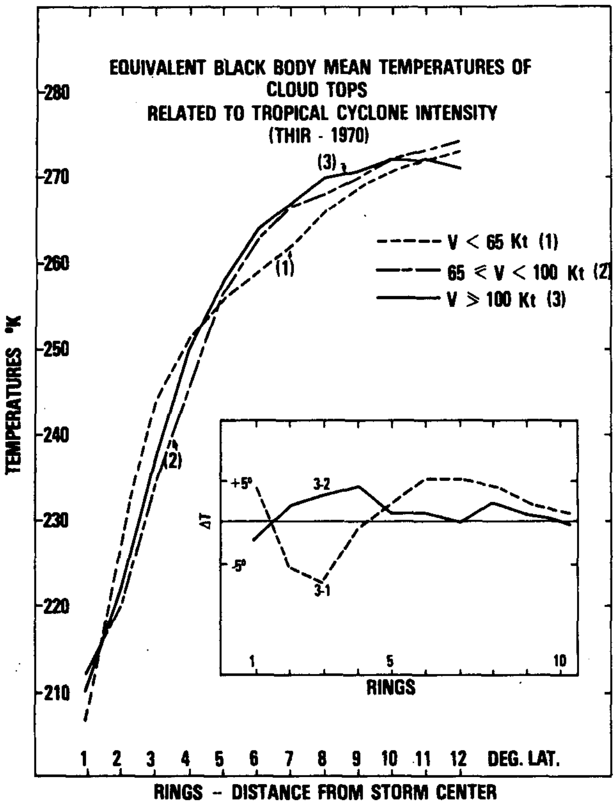

FIG. 3. Comparison of mean temperatures of cloud tops around 1970 tropical cyclones of the western North Pacific: 15 storms with maximum winds < 65 kt (broken line); 13 typhoons with maximum winds < 100 kt (dashed-dotted line); and 14 typhoons with maximum winds equal or > 100 kt (solid line). The insert contains graphs of the differences in temperatures of the latter and the two weaker categories. The rings are illustrated in Fig. 1.

6–10, the hurricanes had higher mean T_{BB}. That is, the T_{BB} 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 been observed frequently by aircraft reconnaissance and in satellite imagery (Shenk and Rodgers, 1978). The subsidence dissipates many of the clouds at distances > 650 km from the center and the higher mean T_{BB} in these regions are observed because the satellite sensor measures the T_{BB} of the sea surface in areas of no clouds.

A similar test was made with the 1970 Pacific Ocean tropical cyclones. The composited mean T_{BB} for 14 typhoons (current maximum wind $V_0 \geq 100$ kt), 13 typhoons (65 kg $\leq V_0 < 100$ kt) and 15 weaker storms ($V_0 < 65$ kt) are compared in Fig. 3. The comparison between the weak storms and those with maximum winds > 99 kt is similar to that of the 1969 Atlantic storms except for ring 1 where the T_{BB} for typhoons are higher. This reflects the large cloud-free eyes of several of the typhoons and the fact that the Nimbus 4 THIR had higher resolution than the Nimbus 3 MRIR. If values for ring 1 are ignored, intense storms are again colder for the inner four rings and warmer at greater radii (dashed line, Fig. 3 insert).

The comparison between the typhoons of moderate intensity with the very intense typhoons (solid line, Fig. 3 insert), however, gave contradictory information. An examination of the individual cases involved showed the moderate intensity storms were biased toward intensification and the intense storms toward weakening or little change. This is especially significant because it suggests that the mean T_{BB} are also an index of the rate of change of storm intensity.

The relationship of T_{BB} to rate of change of storm intensity was investigated by stratifying the storms according to wind intensity changes. Fig. 4 shows composited T_{BB} means for cyclones stratified according to intensity changes during the succeeding 24 hours. Four categories are used: 1) intensifying (V_0 increase $\geq$ 10 kt), 12 cases; 2) weakening

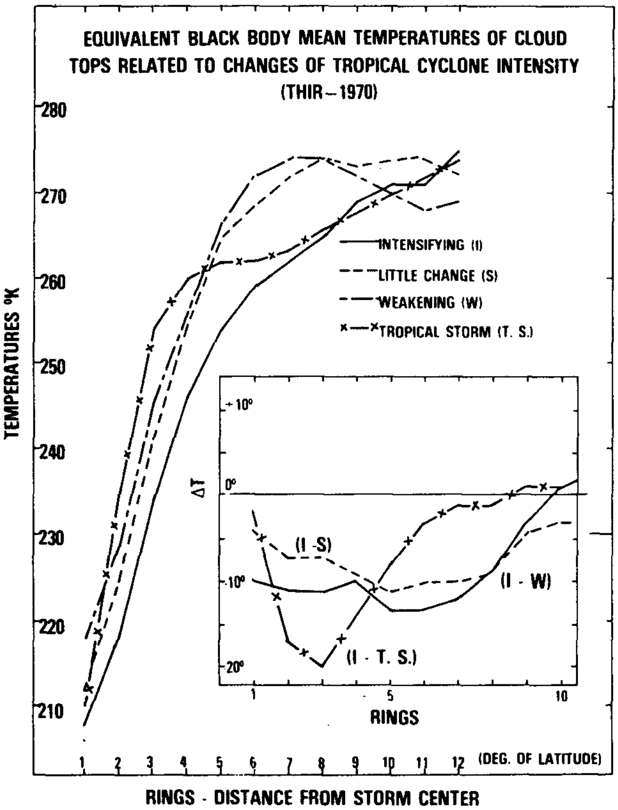

FIG. 4. As in Fig. 3 except that the data are stratified according to change of intensity during next 24 h: maximum winds increasing 10 or more kt (I), maximum winds changing less than 10 kt (S), maximum winds decreasing 10 or more kt (W), and storms which never reached hurricane intensity (T.S.). Only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

(V_0 decrease $\geqslant$ 10 kt), four cases; 3) little change (V_0 change $<$ 10 kt), six cases; and 4) five tropical cyclones which did not reach typhoon intensity. The cases in categories 1, 2 and 3 all reached typhoon intensity. We can note that the storms with the greater rate of intensification are associated with the lower mean T_{BB} in all rings outward through ring 9. The intensifying storms are ~18 K colder in rings 2–4 than the storms that never reached typhoon intensity, ~10 K colder in rings 1–8 than the weakening storms and 5–10 K colder than the storms with little change in intensity.

The time lag between the mean T_{BB} and maximum wind of several tropical cyclones examined further supports the hypothesis that T_{BB} serves as a predicator of wind changes. Fig. 5 illustrates a time lag between the T_{BB} and the change of the maximum winds in 1970 Pacific Typhoons Billie and Hope. The lowest mean T_{BB}, which may be said to represent maximum convection, of Billie occurred two days before the wind maximum was reached and that of Hope occurred more than one day prior to the wind maximum. Similar data examined in other storms suggest that the wind changes lag the T_{BB} changes by 24–36 h.

Fig. 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 Fig. 5, represents convection. There is a striking similarity in the time lag between maximum convection and the maximum winds of the storm in the two illustrations.

The results of these comparisons of the mean T_{BB} and storm intensity strongly suggest that the cloud top T_{BB} near the tropical cyclone center may serve as an index for both 1) current storm intensity, and 2) future storm intensity. This dual relationship is further explored in the succeeding section where equations are developed for predicting storm intensities 24 h in advance.

4. Development of predictive equations

Results of the analyses reported in Section 3 demonstrate that both current and future storm intensities are a function of the mean T_{BB}. These results also suggest that the relationship between the mean T_{BB} and the future intensity varies with at least the latitude of the storm, season of the year, sea temperatures, lapse rate in the ambient atmosphere and past changes in storm intensity. Therefore, it appears there is a need to either stratify the data into several classes or use several predictors to account for the various effects.

The limited number of cases for which good data were available emphasized the need, however, for special care in selection of techniques used in developing the predictive equations. Instead of using a strictly statistical approach in seeking a solution, potential predictors were preselected after use of a combination of physical reasoning based on re-

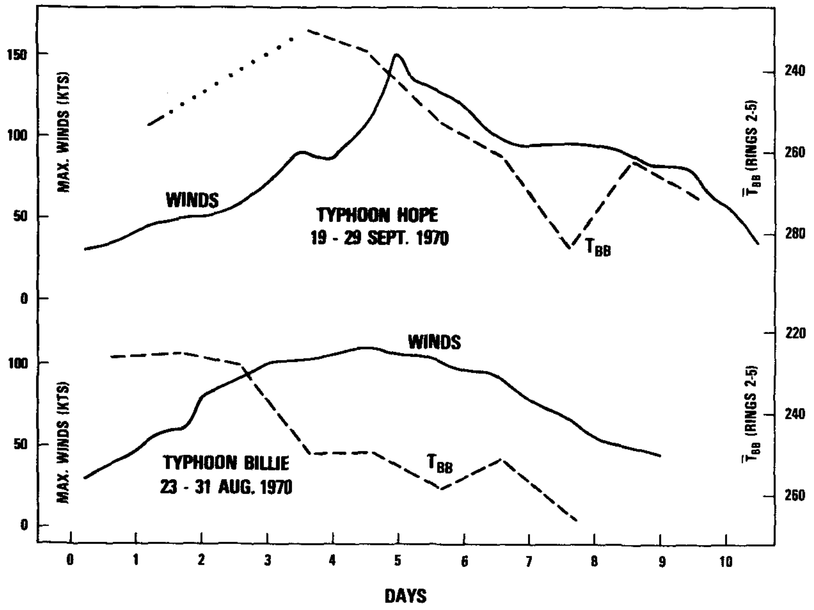

FIG. 5. Temporal changes of mean equivalent blackbody temperatures (rings 2–5, Fig. 1) and maximum winds of Typhoons Hope (September 1970) and Billie (August 1970). The maximum wind changes lag the temperature changes in both cases. The temperature scale is inverted to show the lower temperatures at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

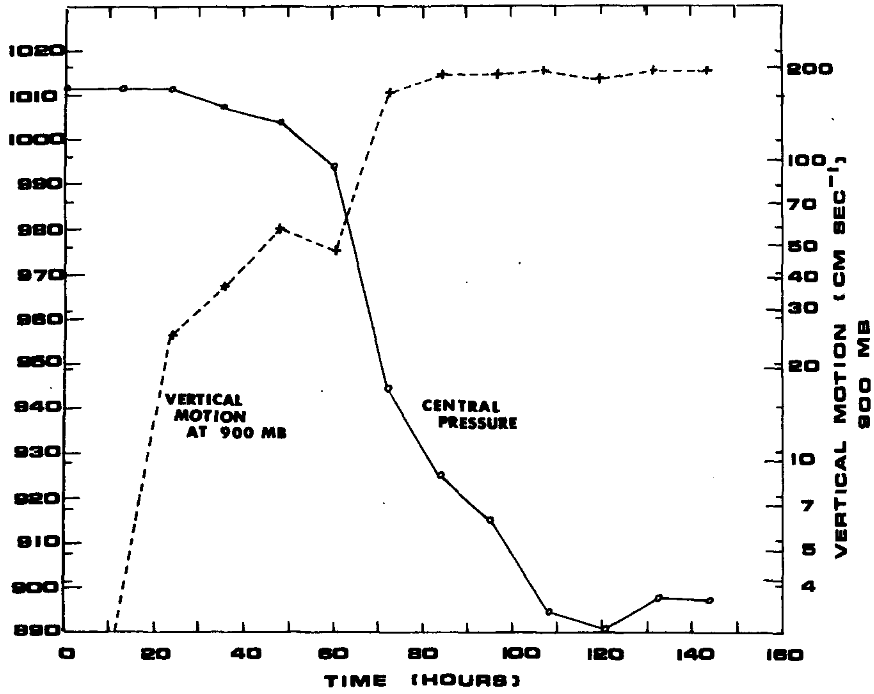

FIG. 6. Comparison of vertical motion and central pressure in a model hurricane showing lag with time (Rosenthal, 1978).

sults of research on tropical cyclones of the last 20 years and statistical type analyses such as those presented in Section 3. Furthermore, because of the concern that the use of a large number of predictors in the equations would lead to unstable solutions which would provide poor forecasts when the predictive equations were applied to independent data, the arbitrary decision was made that not more than four predictors would be used.[4] This required special care in selecting the predictors. The mean T_{BB} parameter to be used in each case was identified by examining data arranged in a systematic fashion (e.g., such as in Fig. 4) or by study of previously calculated correlation coefficients.

It was believed that by using only predictors that seem to have a close physical relationship with the parameter to be predicted that the predictive equations developed with even a relatively few cases would likely be stable and apply to other storms. To further insure that the predictors selected on the basis of physical reasoning and statistical deductions were truly related with the parameter to be predicted and not just correlated by chance, all forecast equations developed were tested with independent data (i.e., data not used in the preliminary analyses to preselect the predictors nor used in the development of the regression equations).

Besides the mean T_{BB} parameter, the current maximum wind (V_0) and the change in maximum winds during the preceding 24 h (ΔV_{-24}) were used as predictors. In addition, parameters putting additional emphasis on the degree of organization of the convection were considered in some of the equations. This was usually a parameter measuring the variability of the mean T_{BB} in one or more of the rings ($\sigma_{n,m}$, where the subscripts refer to the identifiers of rings). Once the predictors had been preselected, a modified screening regression approach was used in developing the equations in order to determine which of the terms contributed most and also to determine just how much reduction in variance occurred as each new predictor was added to the equation.

Stratification of the storms into two groups ($V_0 \leq 65$ kt and $V_0 > 65$ kt) produced better results than single grouping of all storms. Fifty-eight cases from the 1970 western North Pacific tropical cyclones were used as dependent data for developing the following equations. The first three regression equations are:

$$\text{Weak storms} \quad \Delta V_{+24_w} = 143.75 - 0.594\bar{T}_{2,3} + 0.389\Delta V_{-24} \qquad (2)$$

$$\text{Strong storms} \quad V_{+24_s} = 227.86 - 0.76\bar{T}_{1,2,3} + 0.499\Delta V_{-24} + 0.398V_0 \qquad (3)$$

---

[4] In equations tested and used in this report, three predictors at most were used.

All storms
$$V_{+24_a} = 146.6 - 1.669\sigma_{1,2} + 0.855V_0 - 0.513\bar{T}_1. \tag{4}$$

Because of the strength of the relationship of V_{+24} with the satellite measured mean T_{BB}, several equations were developed for use with satellite data alone:

Strong storms
$$V_{+24_s} = 378.51 - 1.225\bar{T}_{1,2,3} \tag{5}$$

Strong storms
$$V_{+24_s} = 390.72 - 1.246\bar{T}_{1,2,3} - 0.506\sigma_3 \tag{6}$$

Weak storms
$$\Delta V_{+24_w} = 167.16 - 0.682\bar{T}_{2,3} \tag{7}$$

All storms
$$V_{+24_a} = 200.51 - 2.213\sigma_{1,2} - 0.381\bar{T}_{2,3}. \tag{8}$$

Here the symbols are defined as follows:

ΔV_{+24_w}	predicted change in maximum wind speed (kt) during a 24 h period after satellite observation for storm whose current maximum winds are ≤65 kt
V_{+24_s}	predicted maximum wind speed (kt) 24 h after satellite observation for storm whose current maximum winds are >65 kt
V_{+24_a}	predicted maximum wind speed (kt) 24 h after satellite observation for storms of any intensity
$\bar{T}_1$	mean T_{BB}(K) for area 0–111 km about the storm center (ring 1)
$\bar{T}_{2,3}$	mean T_{BB}(K) for area 111–333 km about the storm center (rings 2 and 3)
$\bar{T}_{1,2,3}$	mean T_{BB}(K) for area 0–333 km about the storm center (rings 1, 2 and 3)
ΔV_{-24}	change in maximum wind speeds (kt) of the storm during the 24 h preceding satellite observation
V_0	the current maximum wind speed (kt) in the storm at the time of satellite observation
$\sigma_{1,2}$	the standard deviation (K) of the mean T_{BB} of all sectors contained in rings 1 and 2
σ_3	the standard deviation (K) of the mean T_{BB} of all sectors contained in ring 3.

TABLE 1. Correlation coefficients for weak storm cases dependent data (independent data).

	V_{+24}	ΔV_{+24}	V_0	ΔV_{-24}
$\bar{T}_{2,3}$	−0.547 (−0.472)	−0.647 (−0.300)	−0.068 (−0.273)	−0.291 (0.393)
ΔV_{-24}	0.504 (0.482)	0.450 (0.213)		
V_0	0.625 (0.465)	0.177 (0.275)		0.304 (0.398)

Reduction in variance of ΔV_{+24_w} dependent data

Predictors	$\bar{T}_{2,3}$	$\bar{T}_{2,3}$; ΔV_{-24}
Reduction in variance	0.42	0.49

TABLE 2. Correlation coefficients for strong storms dependent data (independent data).

	V_{+24}	ΔV_{+24}	V_0	ΔV_{-24}
$\bar{T}_{1,2,3}$	−0.781 (−0.725)	−0.589 (−0.642)	−0.392 (−0.274)	−0.489 (−0.548)
σ_3	−0.056	−0.286	−0.197	−0.407
ΔV_{-24}	0.662 (0.697)	0.655 (0.446)	0.130 (0.475)	
V_0	0.551 (0.556)	−0.191 (−0.144)		0.130 (0.475)

Reduction in variance of V_{+24_s} dependent data

Predictors	$\bar{T}_{1,2,3}$	$\bar{T}_{1,2,3}$; ΔV_{-24}	$\bar{T}_{1,2,3}$; ΔV_{-24}; V_0
Reduction in variance	0.61	0.71	0.77

Table 1 lists the correlations between the various parameters used as predictors with the quantities to be predicted, and with each other for the weaker storms. Table 2 lists the correlation data for intense storms. Eqs. (2) and (7) were developed to predict the change in maximum wind speeds during the next 24 h rather than the maximum wind speed for two reasons: 1) the correlation between $\bar{T}_{2,3}$ was higher with ΔV_{+24} than with V_{+24} and 2) in the typhoon service, operational procedures are such that for weak storms the forecaster is believed in many cases to have a better estimate of whether a storm is intensifying than of the absolute value of the maximum winds. Of course, by adding V_0 to both sides of the equations, one can put them in the same format as the other equations.

The great value of Eqs. (4)–(8) is that no past history of the storm is needed. This provides a means of making reliable forecasts over isolated ocean basins. The current satellite imagery can be used for a general classification (over/under 65 kt) and the infrared data may be used to develop the necessary T_{BB} parameters. By using the Dvorak technique (Dvorak, 1975), one can also obtain V_0 from satellite data [Eq. (4)].

Errors of forecasts made with the equations were compared with those obtained by techniques frequently used in tropical cyclone intensity forecasting: persistence (NC) [assumes no change during the forecast period], and persistence of change (P) [assumes the change during forecast period is the same rate as the change during the preceding period]. Results of this comparison for both the dependent and independent data series are summarized in Table 3. The independent series were from the 1973 and 1974 western North Pacific tropical cyclones.

5. Discussion of results

In the weak tropical cyclone set, Table 3 reveals that Eqs. (2) and (7) produce better forecast results compared to those from persistence techniques not only for the dependent data which would be expected but also for the independent data sets. The difference between regression and persistence (NC)

TABLE 3. 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 ($V_0 \leq 65$ kt)				
2	24	8.6	−4.0	−4.2	33	12.6	−4.2*	−0.6
4	24	10.2	−2.4	−2.6	33	14.2	−2.4	1.0
7	24	9.6	−3.0	−3.2	33	12.8	−4.0*	−0.4
8	24	24.9	12.3	12.1	33	25.0	+8.2	+11.8
				Intense tropical cyclones ($V_0 > 65$ kt)				
3	34	9.4	−7.5	−2.6	20	16.1	−3.1	−6.9*
3 (−11 kt)					20	11.8	−7.4*	−11.2*
4	34	12.1	−4.8	0.1	20	14.7	−4.5*	−8.3**
5	34	11.4	−5.5	−0.6	20	18.8	2.0	5.6
5 (−11 kt)					20	15.6	−3.6	−7.4*
6	34	10.8	−6.1	−1.2	20	18.7	1.9	5.5
6 (−11 kt)					20	14.9	−4.3	−8.1*
8	34	21.1	4.2	9.1	20	17.4	−1.8	−5.6
				All storms				
2 & 3	58	9.1	−6.0	−3.2	53	13.9	−3.8*	−3.0**
4	58	11.4	−3.7	−0.9	53	14.4	−3.3*	−2.5
8	58	22.7	7.6	10.4	53	22.1	4.4	+5.2

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 h would be the same as the change during the previous 24 h.
* Differences significant at 1% level.
** Differences significant at 5% level.

results in the independent data set is significant at the 1% level. Eq. (8) yielded only fair results; Eq. (4), however, produced strikingly good results considering that satellite data alone were used in forecast parameters[5] and that this equation applied to both weak and strong storms.

The intense tropical cyclone [Eqs. (3), (5) and (6)] provide good forecasts in the dependent data set but only Eq. (3) gives results better than persistence with the independent data set. However, a bias (see Section 6) is believed to exist in the wind information of the independent set and causes the intensity forecasts by the regression equations to be about 11 kt too high in the mean. When this bias is removed from the forecasts for the independent data set, Eqs. (3), (5) and (6) are better than persistence. Significance at the 1% level is prominent in several comparisons. Eq. (4) shows superiority even without the bias removed.

For all storms combined Eq. (4) gives better results than persistence techniques. They are only slightly weaker than results from Eqs. (2) and (3) combined. This is particularly significant in that forecasts from Eq. (4) can be made using only satellite data. Eq. (8) does not produce results of comparable quality.

The regression equations for the intense and weak tropical cyclones have yielded results throughout the dependent data set which are −0.1 to 7.5 kt better than the persistence results [Eq. (8) excepted]. The independent data set results are −5.6 to 8.3 kt better. When the bias error is applied for Eqs. (3), (5) and (6) in the independent data set the regression results are 3.6–11.2 kt better than the persistence results.

One of the objectives of this investigation was to determine whether the mean T_{BB} were strongly related to the current and future wind speeds and whether they had predictive value. The fact that the regression equations outperform persistence for the independent series suggests that the T_{BB} do contain predictive information over and above that contained in the current and previous wind data. Nevertheless, the fact that equations using ΔV_{-24} and V_0 produced superior forecasts to those which used only the mean T_{BB} and its derivatives, makes it pertinent to ask if the skill shown in Eqs. (2), (3) and (4) is primarily due to the use of wind information. The answer to this question is contained in Tables 1 and 2.

For the weak storms in the dependent data series,

---

[5] Assumes that V_0 can be obtained by the Dvorak or some similar technique.

the highest correlation with the winds was between $\bar{T}_{2,3}$ and ΔV_{+24}. For the independent data the highest correlations was with V_{+24} and there were relatively little difference in correlations between it and with $\bar{T}_{2,3}$, ΔV_{-24} or V_0. The reduction in variance was 0.42 when $\bar{T}_{2,3}$ was the sole predictor. Adding ΔV_{-24} as a predictor increased the reduction in variance to 0.49.

$\bar{T}_{2,3}$ is poorly correlated with ΔV_{-24} in the weak series so they should contribute independently to the skill of the regression equation. Note that the sign of this correlation changes between dependent and independent data.

For the strong storms dependent data (Table 2) the correlation between $\bar{T}_{1,2,3}$ with V_{+24} (-0.781) is stronger than that between V_{+24} and either ΔV_{-24} (0.662) or V_0 (0.551). While the correlation between $\bar{T}_{1,2,3}$ and either V_0 or ΔV_{-24} is considerably higher than for the weak storms, these correlations are still lower than the correlations between $\bar{T}_{1,2,3}$ and either V_{+24} or ΔV_{+24} (-0.781 and -0.589 vs -0.392 and -0.489) data. These relationships also hold for the independent data.

In the tests of significance of the differences in the errors by the regression equations and the errors by persistence techniques, consideration was given to the size of the samples of the independent data. There were 33 cases for the weak category selected from 20 different storms from two years. There were 20 cases for the strong category selected from 9 different storms from two years. Most of the cases from the same storm were spaced at intervals $\geq$ 24 h. There were, however, five cases from one storm and three cases from another storm in the strong sample which were approximately at 12 h intervals. For the weak storms there were five storms that contributed two cases and one storm that contributed three cases where the interval was approximately 12 h. Examination of these cases revealed that the standard deviation of the errors of the regression forecasts were much larger for the strong storm cases with the 12 h intervals than for the entire sample. For the weaker storms there was little difference between the standard deviation of the errors for the cases of 12 h intervals and for the entire sample. That is, the data from the individual cases were sufficiently convincing that there was relatively little autocorrelation between the storm cases spaced at 12 h intervals and their inclusion did not alter the effective sample size.

6. Bias in forecast results

The forecast results from Eq. (3) are better for the independent data than those obtained from persistence. However, examination of the errors reveals that the regression equation forecasts maximum winds 11.3 kt too high in the mean for the independent cases of 1973 and 1974. This bias was calculated by taking the algebraic mean[6] of the forecast errors. The equations and data were tested to determine the cause of the bias. The following were checked for possible biasing effects: 1) satellite sensor calibration variation; 2) time of year of storm occurrence; 3) location of storm; and 4) operation and best track estimates of maximum wind speeds.

To check the sensitivity of results from the equations to possible bias corrections, the constant term of Eq. (3) was reduced by various amounts ranging from 8 to 17 kt. This variation caused only minor variations in the mean of the absolute values of the errors for the independent series (12.7–11.6 kt which compares with 16.1 kt when no bias was applied). This suggests that a bias correction in the range 8–17 kt that was well substantiated might be used to adjust the constant in Eq. (3) when it was used with data from the 1973 and 1974 seasons. Other equations were tested with similar results.

The biasing effect caused by using T_{BB} observations from different satellites was minimum. The upper and lower limits of the mean T_{BB} values and their range in the tropical cyclones as measured in the storms by Nimbus 3, 4 and 5 agreed within $\leq 2°C$.

Seasonal, latitudinal and longitudinal variation between the dependent and independent data sets resulted in differences which would account for only a few knots (-2 to 4 kt) difference in forecast for the dependent and independent data and even then only for a few storms. The effect of these factors is not believed, therefore, to be of sufficient magnitude to account for the large bias found to exist.

The operational estimates of maximum wind, however, could account for the bias. Atkinson and Holliday (1977) discuss the "considerable uncertainty involved in existing equations" for estimating maximum winds and report changes in procedures at the Joint Typhoon Warning Center at Guam (JTWC) that may affect results of our experiment. Table 4 compares the maximum wind calculated for a range of central pressures (P_c) from the following three equations (Atkinson and Holliday, 1977):

Equation by Atkinson and Holliday

$$V_{m_1} = 6.7(1010 - P_c)^{0.644} \qquad (9)$$

Equation by Takahashi

$$V_{m_2} = 13.4(1010 - P_c)^{0.5} \qquad (10)$$

Equation by Takahashi (high lat.)

$$V_{m_3} = 11.5(1010 - P_c)^{0.5}. \qquad (11)$$

Here P_c is the central pressure (mb) of the storm and V_m the maximum wind speed (kt). When these

---

[6] The errors listed in Table 3 are all means of absolute values of individual errors.

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	147	

equations are applied to the independent data set cases the mean difference between the results from Takahashi's and Atkinson and Holliday's equations is near 10 kt. Holliday[7] reports that Eq. (9) was used for developing most of the "best track" information for the 1973 and 1974 years while Eqs. (10) and (11) were used in 1970. These results suggest that the changes in procedures at JTWC for estimating wind maxima may account for most of the bias found.

To further test the hypothesis that the bias is due to change in procedures for obtaining maximum winds, the 1973, 1974 data were used dependently to develop equations similar to Eqs. (3) and (6). These new equations

$$V_{+24_i} = 243.91 - 0.885\bar{T}_{1,2,3} + 0.385\Delta V_{-24} + 0.424V_0, \quad (12)$$

$$V_{+24} = 395.3 - 1.333\bar{T}_{1,2,3} - 0.404_{\sigma_3}, \quad (13)$$

were substracted from Eq. (3) and (6), respectively, and the results simplified to provide

$$V_{+24_s} - V_{+24_i} = 8.5 + 0.125(\bar{T}_{1,2,3} - 210) + 0.114\Delta V_{-24} - 0.026(V_0 - 65), \quad (14)$$

$$V_{+24_s} - V_{+24_i} = 13.078 + 0.087(\bar{T}_{1,2,3} - 210) - 102(\sigma_3 - 6). \quad (15)$$

When Eq. (14) is solved using representative values ($\bar{T}_{1,2,3} = 230$ K, $V_0 = 90$ kt) the result is 10.9 kt. When Eq. (15) is solved using representative values ($\bar{T}_{1,2,3} = 230$ K, $\sigma_3 = 10$ K) the result is 13.7 kt. Forecasts made by Eq. (3) with the constants reduced by 11.3 and those made with Eq. (12) have a correlation coefficient of 0.99. These various numbers compare favorably with the 11.3 kt bias found and are all within the range 8–17 kt. Thus, the results lend strong support to the contention that much of the bias in Eq. (3) exist due to the change in procedures for estimating wind maxima when preparing the "best track" information at JTWC.

7. Simulated operational test results

Simulated operational tests were made using the regression equations (2), (3) and (4). Wind data from typhoon advisories for the 1973, 1974 storms were incorporated as input parameters in place of best track winds. The results produced even greater increases in errors in persistence forecasts than in the regression forecasts. The regression results could not be readily compared with the JTWC forecasts for these test cases. JTWC advisory (forecast) times did not coincide exactly with satellite observation times and not all JTWC forecasts were available. To the extent information was available, it was possible to determine that the JTWC forecast errors of the test cases greatly exceeded their mean absolute error of 13.5 kt for the entire 1973 and 1974 seasons. The JTWC forecast errors were also larger than the mean errors of the regression equations for the cases where adequate comparisons could be made. It appears from these results as well as those discussed in Section 5 that the regression equations will yield better forecasts than other techniques being used.

8. Conclusions

This investigation demonstrated that there is a strong relationship between satellite measured T_{BB} of cloud tops near the core of the tropical cyclones and both the current and future storm intensity. This was demonstrated for four different seasons of data (one in the Atlantic and three in the Pacific area). The statistical correlation, moreover, reveals that the future intensity (V_{+24}) is more closely related than the current intensity (V_0) to the mean T_{BB} (correlation −0.781 vs 0.392, Table 2).

The regression equations provided forecasts superior to those of persistence techniques when applied to independent data. The equations produced better results than other techniques in simulated operational tests. The results are sufficiently convincing to warrant use of the equations as experimental forecast tools. It is particularly important that such good results are obtained from quantified T_{BB} data, a parameter readily obtainable from a single satellite observation.

Further testing is recommended before implementing the technique in operational forecasting routines because of the limited sample size which was available in this investigation. It would be desirable to expand the investigation to include more cases as well as other tropical cyclone basins. The data contained in this report appear convincing,

---

[7] Personal communication.

however, that there is a relationship between T_{BB} and future maximum winds in tropical cyclones that is strong enough to have predictive value.

REFERENCES

Arnold, E. P., 1977: Tropical cyclone cloud and intensity relationships. Atmos. Sci. Paper No. 277, Colorado State University, 154 pp.

Atkinson, G. D., and C. R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the western North Pacific. *Mon. Wea. Rev.*, **105**, 421–427.

Dvorak, V. R., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, 420–430.

Dunn, G. E., and B. I. Miller, 1960: *Atlantic Hurricanes*. Louisiana State University Press, 123 pp.

Gentry, R. C., 1966: Nature and scope of hurricane damage. *Proceedings Hurricane Symposium*, Amer. Soc. Oceanogr., 229–254.

Griffith, C. G., W. L. Woodley, P. G. Grube, D. W. Martin, J. Stout and D. N. Sikdar, 1978: Rain estimation from geosynchronous satellite imagery—visible and infrared studies. *Mon. Wea. Rev.*, **106**, 1153–1171.

Howard, R. A., J. E. Matheson and D. W. North, 1972: The decision to seed hurricanes. *Science*, **176**, 1191–1201.

Hubert, L. A., A. Timchalk and S. Fritz, 1969: Estimating maximum wind speed of tropical storms from high resolution infrared data. ESSA Tech. Rep. NESC50, 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.

Nimbus 3 User Guide, 1969: Nimbus Project, National Space Science Data Center, Goddard Space Flight Center, Greenbelt, MD, 237 pp.

Nimbus 4 User Guide, 1970: Nimbus Project, National Space Science Data Center, Goddard Space Flight Center, Greenbelt, MD, 214 pp.

Nimbus 5 User Guide, 1972: ERTS/Nimbus Project, National Space Science Data Center, Goddard Space Flight Center, Greenbelt, MD, 162 pp.

Riehl, H., 1954: *Tropical Meteorology*. McGraw-Hill, 392 pp.

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

Shenk, W. E., and E. B. Rodgers, 1978: Nimbus 3/ATS 3 observations of the evolution of Hurricane Camille. *J. Appl. Meteor.*, **17**, 453–476.

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

——, 1973: Annual Typhoon Report. U.S. Navy Report, Guam, 94 pp.

——, 1974: Annual Typhoon Report, U.S. Navy Report, Guam, 113 pp.