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STATISTICAL FORECASTS OF TROPICAL CYCLONE INTENSITY FOR THE NORTH ATLANTIC BASIN

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ABSTRACT. This study describes the derivation of a system of statistical regression equations for the prediction of tropical cyclone intensity changes over the Atlantic tropical cyclone basin. The study is part of a larger effort to increase operational skill in the prediction of tropical cyclone intensity. The present study is limited to predictors derived from climatology and persistence. However, extensions of the study will include the use of predictors derived from environmental data fields.

Independent data tests of the system over the 1976 and 1977 Atlantic hurricane season disclose a skill comparable to the official forecast of intensity changes. However, based on mean absolute errors, the model improves slightly on the official forecast for the 12 and 24h forecast periods while the reverse is true for the 48 and 72h forecast periods. This suggests that the forecaster has the ability to inject some "skill" over climatology and persistence into the extended range forecasts of tropical cyclone intensity.

1. INTRODUCTION

As documented by Hope and Neumann (1977), numerous statistical and a few numerical models for the prediction of tropical cyclone motion are in operational use at the various worldwide tropical cyclone forecast centers. In contrast, a survey of the literature discloses only one operational statistical model (Elsberry, et al., 1974) for the prediction of tropical cyclone intensity changes.

The disparity is due to the difficulty in establishing cause and effect relationships for intensity changes. For example, the motion response of tropical cyclones to changes in environmental "steering" is well documented (George and Gray, 1976) and significant predictor/predictand correlations can be established. However, no such well-marked correlations have been established in the case of intensity changes. Part of the problem is related to the fact that the historical documentation of tropical cyclone intensity leaves much to be desired when compared to track documentation.

Michaels (1974) used a relatively short period of record of Atlantic aircraft reconnaissance data to establish a five-degree square conditional climatology of Atlantic tropical cyclone intensity changes. These data and other sources were used by Neumann et al. (1978) as the basis of a revised Atlantic tropical cyclone climatology. The latter tracks and intensities were transferred to magnetic tape by Jarvinen and Caso (1978) and together with extensive computer files of upper-air data available to the National Hurricane Center, provide a data set for a renewed effort to establish an operational statistical-synoptic model for the prediction of tropical cyclone intensity changes for the Atlantic.

The present study will limit itself to predictors selected from climatology and persistence. Such a model, designated by the acronym CLIPER (CLImatology and PERsistence) was developed by Neumann (1972) for the statistical prediction of tropical cyclone motion. CLIPER not only provides a convenient "benchmark" upon which to base the skills of more sophisticated models, but also stands alone as excellent guidance on the prediction of motion within the easterlies. Recent statistical models developed at the National Hurricane Center use the output from the CLIPER model as input to higher-echelon statistical models which modify the CLIPER forecast according to current and forecast environmental steering forces.

The development of the current model for the prediction of tropical cyclone intensity will parallel the development of CLIPER. The initial base model has been designated by the acronym SHIFOR (Statistical Hurricane Intensity FORecast). Like CLIPER, it is expected to provide a convenient benchmark upon which to base the skills of more sophisticated models as well as the "official" forecast of intensity changes. The next phase of this study (not reported on here) will attempt to modify the SHIFOR forecasts based on environmental data fields.

Another potential source of information for the objective prediction of intensity changes is the weather satellite. This would include digitized infrared data as well as gridded cloud coverage algorithms such as developed by Waters et al. (1976). Studies using such data are being conducted by the National Aeronautics and Space Administration and the National Environmental Satellite Service. Gentry et al. (1978), for example, develop regression equations which relate infrared temperatures with intensity changes. Dvorak (1975), on the other hand, describes a technique to forecast tropical cyclone intensity using visible satellite pictures. Apart from the weather satellite, Gray (private communication, 1979) proposes relating upper air temperature anomalies above the storm, as measured by aircraft, to surface intensity changes. Hopefully, these various "bits"of predictive information from such sources as SHIFOR, environmental data fields, digitized satellite data, etc. can be statistically consolidated so as to increase the skill in the prediction of tropical cyclone intensity changes.

2. DATA SOURCE

The data used in this study were extracted from the National Hurricane Center's North Atlantic tropical cyclone data tape (Jarvinen and Caso, 1978). The tape contains the dates, tracks, wind speeds, and central pressure values (if available) for all tropical cyclones occurring over the 92-year period, 1886 through 1977. The information on this tape was recorded at 6-hourly intervals and was based on post analyses of all available data. These are referred to as "best-track" and "best-wind" data.

Two measures of intensity of a tropical cyclone are wind speed and central pressure.[1] These parameters are highly correlated, but substantial deviations in the maximum wind speed value exist for storms with the same central pressure value. For this reason both values have been recorded. Of the two values, central pressure would be a more logical forecast parameter because it is more conservative and can generally be measured easier than the maximum wind. However, the amount of central pressure information is small, especially prior to the introduction of aircraft reconnaissance. On the other hand, maximum wind has been measured or estimated by multiple means for all of the tropical cyclones even though doubt exists in many of the cases as to whether the maximum wind value was really obtained.

Storm data prior to 1900 were not used because of fragmented intensity documentation. The final data set was broken into two parts: 1900 through 1972, which represents the dependent data set from which the regression equations were generated and 1973 through 1977 or the independent data set, upon which the equations were tested.

Several constraints were placed upon both data sub-sets:

(1) Only those 6-hour positions within the geographical area bounded by 45 degrees latitude on the north, the equator on the south, five degrees longitude on the east, and the North, Central, and South American Continents on the west, were accepted.

(2) Only those 6-hour positions which were not within 30 n.mi. of land and had previous 6- and 12-hour positions not within 30 n.mi. of land were accepted.

(3) All wind values, including those at -12 hours, had to equal or exceed 35 knots (i.e., tropical storm strength or greater).

(4) If a storm moved inland and later moved out over water, those

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[1] This is the pressure measured or estimated at sea-level by various means.

six hour positions that could not meet constraints 1, 2, or 3 were eliminated. For example, a storm that moved out of the Caribbean Sea, passed over Western Cuba, and moved into the Gulf of Mexico would have had the Caribbean Sea and Gulf of Mexico 6-hour track and intensity values included in the data set. The values corresponding to the portion of the track affected by Western Cuba would not have been added.

Figure 1 is a plot of the spatial distribution of data for generating a 12-hour prediction equation. The center of each circle represents the initial latitude and longitude. The positions of the storms 12-hours later look very similar to this distribution except many of the circles are closer to land. Figure 2 is similar to figure 1, but

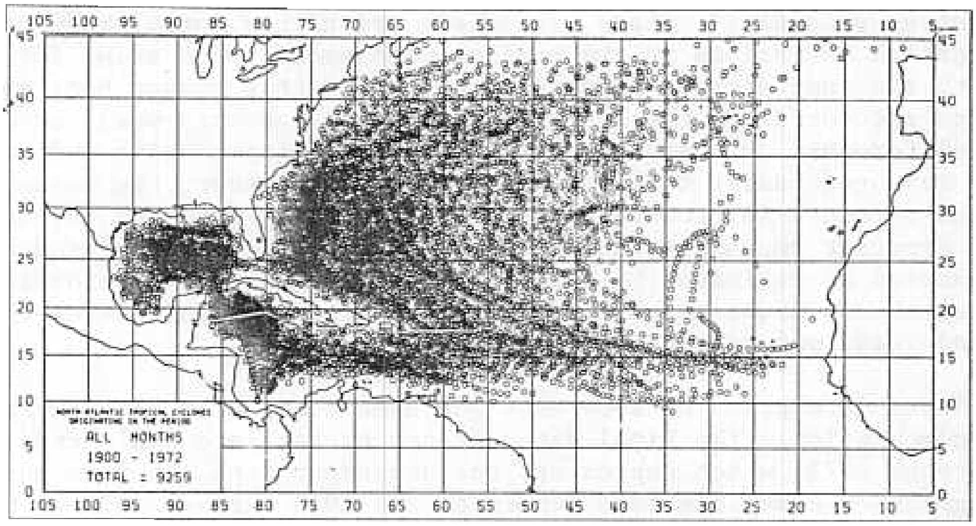


Figure 1. Initial positions of data available for generating a 12-hour prediction equation.

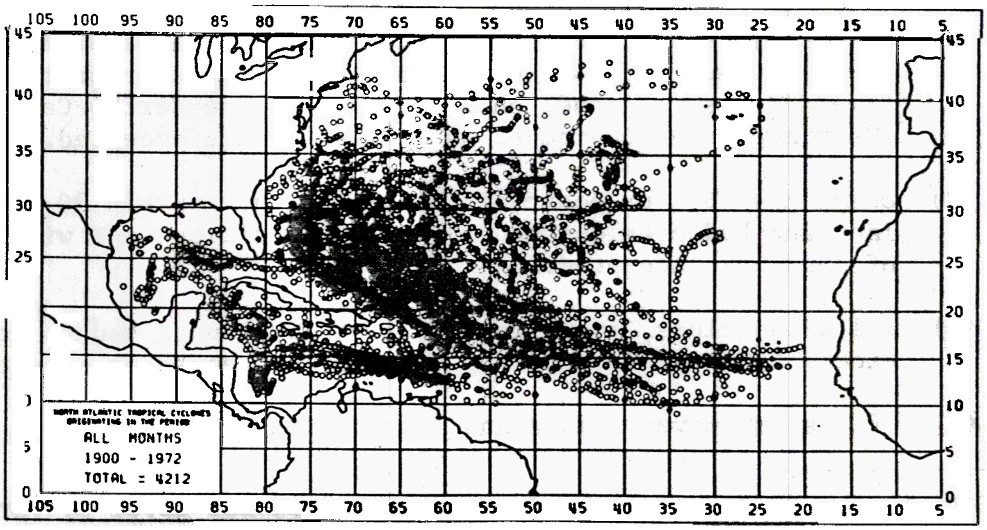


Figure 2. Same as figure 1 except for 72-hours

represents the data available for generating a 72-hour prediction equation. It can be noted that the numberof cases has been substantially reduced. This occurs because many of the storms, 72-hours later, either dissipated or moved outside of the artificial boundaries.

3. DERIVATION OF PREDICTION EQUATIONS

Multivariate regression analysis has been widely used in the meteorological profession for a number of years. A stepwise regression procedure from the IBM multivariate analysis program was used to develop the prediction equations. An important but often overlooked aspect of multivariate analysis relates to the question of statistical significance. A significance test as described by Neumann et al. (1977), was made and is described in section 7.

A. Predictands

Since current maximum sustained wind speed is reasonably well known, the quantity to be forecast is change (plus or minus) in maximum sustained wind speed for a particular time period. This quantity is then algebraically added to the initial maximum sustained wind speed to produce a forecast value. Although operational forecasts of maximum sustained wind speed are only made for 12-, 24-, 48-, and 72-hours, prediction algorithms were developed for each 12-hour increment through 72-hours. Therefore, six predictands are defined. These, listed along with their means and standard deviations, are given in table 1.

Table 1.--Means and standard deviations of the six predictands (knots) for the total basin

	Mean	Standard deviation	Cases
12h Maximum wind speed change	1.3	7.9	9259
24h Maximum wind speed change	2.6	13.4	7928
36h Maximum wind speed change	4.0	17.8	6785
48h Maximum wind speed change	5.5	21.4	5793
60h Maximum wind speed change	7.0	24.4	4945
72h Maximum wind speed change	8.2	26.8	4212

The mean and standard deviation of the changes in maximum wind speed, in table 1, are seen to increase with time. However, these increases are not linear. A plot of either quantity versus time tends to approach an asymptotic value. This is a reflection of the bounded values of the intensities (i.e., 35 knots to 160 knots). This implies a theoretical speed change range of -125 to +125 knots but, in our sample, it ranged from -75 to +100 knots. The positive skewness of the means is due to the fact that many of the decaying portions of the storms were eliminated by the constraints listed in section 2.

Figure 3 shows the frequency distribution for (a) the observed 12-hour and (b) the observed 72-hour changes in wind speed for the dependent data sub-set (1900 through 1972). The intermediate times are not shown but, have similar distributions. There are several interesting features in these distributions. First, as one might expect, in moving from 12-hour changes to 72-hour changes, the distributions flatten out because of the greater changes in wind speed that can occur through the later times. Secondly, as stated above, the distributions are skewed toward the right (positive). Finally, the most frequent wind speed change in any of the distributions is zero. There appears to be two possible reasons for this latter result. (1) Many of the storms intensify to some maximum wind speed value and maintain this value for long periods of time. The maximum wind speed value actually reached would be a function of environmental flow, storm dynamics, and the interaction of both. (2) Many of the zero wind speed changes may be artificial. For instance, if data were missing, the analyst would tend to keep the same wind speed value until new data suggested a change. One might feel that this would be the rule rather than the exception for the earlier

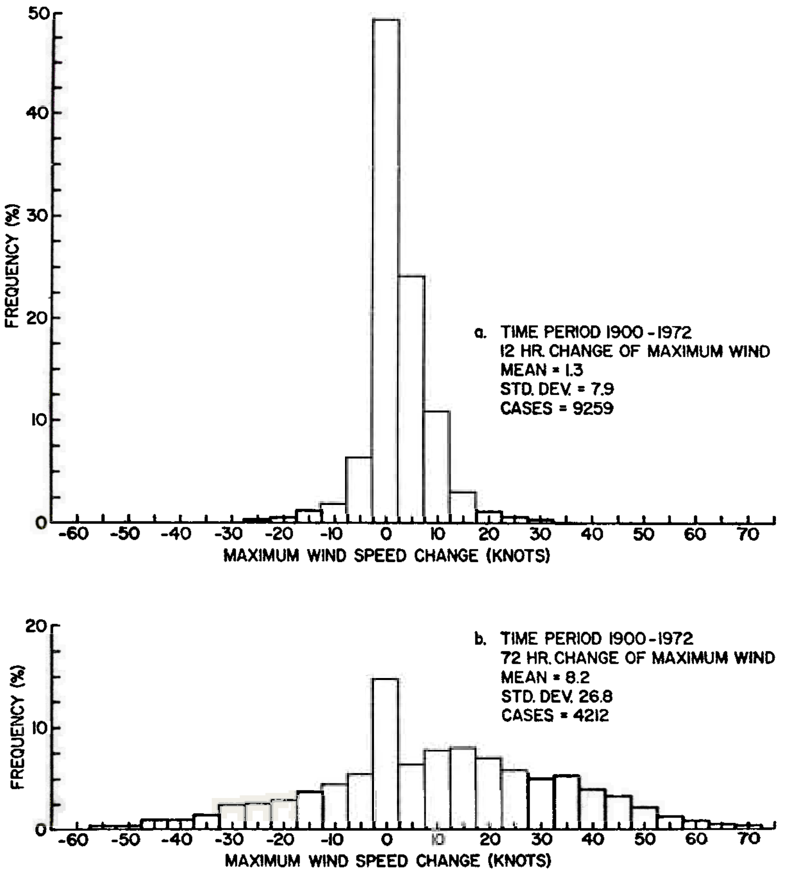


Figure 3. Frequency distribution of (a) the observed 12-hour and (b) the observed 72-hour changes of the maximum wind speed for the time period 1900 through 1972.

part of our record. To investigate this, distributions similar to figures 3a and 3b were constructed for the time periods 1900 through 1945, 1946 through 1977, and 1957 through 1977. The distributions are very similar to the ones for 1900 through 1972. Since our wind speed information is more frequent in the later years, this result suggests that the first reason given is the most likely.

B. The Seven Primary Predictors

Seven primary predictors form the basis of the prediction scheme. These contain information about the tropical cyclone at the initial time as well as 12 hours earlier. Together with their means and standard deviations, the seven primary predictors are identified in table 2.

Table 2.--Means (upper) and standard deviations (lower) of the seven primary predictors

PREDICTOR	SYMBOL	FORECAST PERIOD					
		12h	24h	36h	48h	60h	72h
Day number	P1	254	254	254	254	254	254
		35.7	34.7	33.7	32.7	31.6	30.4
Initial latitude (degrees N)	P2	25.6	25.2	24.8	24.4	24.0	23.7
		7.8	7.5	7.4	7.3	7.2	7.1
Initial longitude (degrees W)	P3	66.0	65.1	64.2	63.3	62.5	61.6
		15.1	14.7	14.3	14.0	13.9	13.7
Average zonal speed past 12h (kt)	P4	-2.2	-2.7	-3.1	-3.4	-3.8	-4.1
		9.2	8.7	8.4	8.2	8.0	7.8
Average meridional speed past 12h (kt)	P5	5.1	4.9	4.7	4.5	4.3	4.3
		5.2	5.0	4.7	4.5	4.4	4.3
Current maximum sustained wind speed (kt)	P6	67.1	67.9	68.4	68.7	68.9	69.0
		24.8	24.7	24.7	24.8	24.8	24.9
Previous 12h change in maximum sustained wind speed (kt)	P7	2.4	2.8	3.2	3.4	3.6	3.7
		7.7	7.4	7.2	7.1	7.1	7.1
Number of cases		9259	7928	6785	5793	4945	4212

Many meaningful trends and patterns can be noted in table 2. For example, as the forecast period increases from 12 through 72 hours the mean initial latitude/longitude position moves toward the southeast. This reflects the fact that many of the later cases have tracks within the deep easterly regime of the tropics. This shift in storm centroid is further reflected by the mean zonal and meridional speeds. The zonal speed (toward the west) increases with time while the meridional speed (toward the north) decreases with time. Inspection of the means of the current maximum sustained wind speed and previous 12 hour change in the maximum sustained wind speed show a slight increase from 12 through 72 hours.

Spatial distributions of the last four quantities in table 2 were analyzed to identify any discontinuities. The data were analyzed using an objective analysis scheme described by Jarvinen (1973). The final values can be considered a weighted mean of those observations located within 111 kilometers of a grid point. No major discontinuities were detected in the four analyses. Figure 4, an example of one of these analyses, shows the spatial distribution of the observed maximum sustained wind speed in knots.

Several important features can be noted in this figure. Most storms that recurve northward reach maximum intensity at or near their recurvature point. Since the mean latitude of recurvature for all months in the North Atlantic is near 30 degrees north (Riehl, 1954, page 352), one would expect a wind speed maximum near this latitude. Indeed, one finds this to be true from 55 degrees west to 80 degrees west. A similar result for the Western North Pacific was reported by Riehl (1972). Two other important maxima occur in the central Caribbean Sea and the central Gulf of Mexico. In these locations storms can move over warm tropical waters without the weakening effects of land. Several minor maximums and minimums occur over the map. Many of these are in the "noise" range. Others could possibly be supported by physical reasoning. However, a study of these smaller scale features is beyond the scope of the present efforts.

C. Secondary Predictors

Seven basic predictors (table 2) have been defined. Because of the computational power and the large sample size available, it was decided to generate third-order equations and investigate the predictive potential of these additional higher order terms. With seven basic or primary predictors, 120 product and cross-product terms can be generated. An initial decision was made to retain only those terms which explained at least one half of one percent of the variance. With this criterion, as few as five terms or as many as eight terms could be retained in the six prediction equations. For programming convenience it was decided to retain ten terms for each equation plus the intercept constant. These were termed ten-predictor equations. The predictors used in each equation are given in table 3. P1 through P7 represent the quantities listed in table 2. For example, table 3 shows that for the 12-hour prediction equation, one of the most important predictors is the product of the day number and the previous 12-hour change in the maximum sustained wind speed. At 72-hours, on the other hand, the dominant predictor is the product of the latitude and the current maximum sustained wind speed.

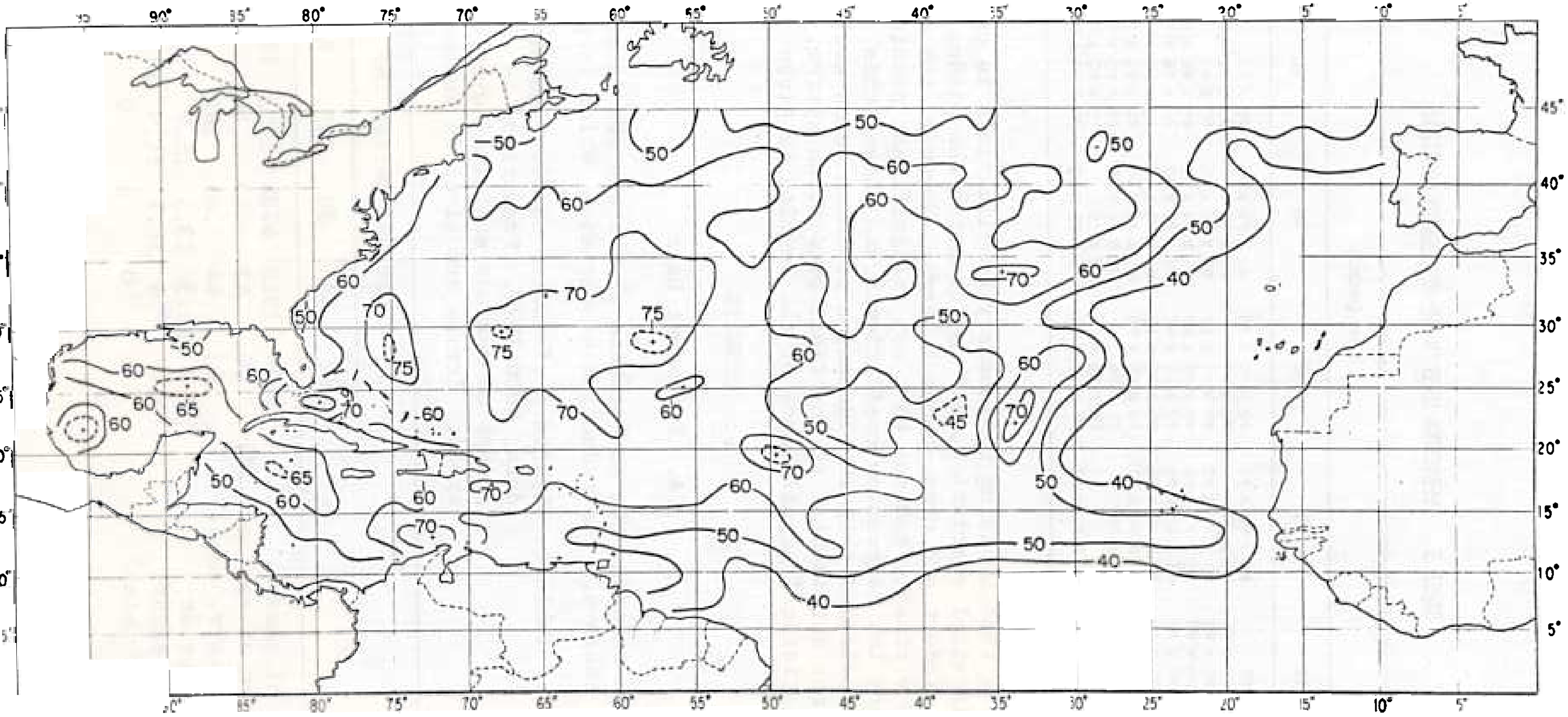


Figure 4. Spatial distribution of the observed maximum sustained wind speed in knots for the time period 1900 through 1972. The location of each of the 9259 cases used in the analysis is indicated in figure 1. The values can be considered a weighted mean of all those observations within 111 kilometers of a grid point. Grid point spacing is 167 kilometers.

TABLE 3 PREDICTORS USED IN THE REGRESSION EQUATIONS

	TIME (HOURS)					
TERM	12	24	36	48	60	72
1	P1 X P7	P2 X P2 X P6	P2 X P2 X P6	P2 X P2 X P6	P2 X P6	P2 X P6
2	P2 X P2 X P6	P1 X P7	P1 X P7	P1 X P7	P1 X P1 X P4	P1 X P1 X P4
3	P7 X P7 X P7	P7 X P7 X P7	P7 X P7 X P7	P6 X P6 X P6	P3 X P7	P5 X P6 X P6
4	P5 X P5 X P6	P5 X P5 X P6	P5 X P6 X P6	P1 X P4 X P6	P5 X P6 X P6	P7
5	P3 X P4 X P7	P6 X P6 X P6	P3 X P4 X P7	P7 X P7 X P7	P3 X P6 X P7	P6 X P7
6	P6 X P6 X P6	P1 X P4 X P6	P1 X P6 X P7	P5 X P5 X P6	P5 X P6	P4 X P4 X P4
7	P4 X P5 X P6	P3 X P4 X P7	P4 X P5 X P6	P1 X P6 X P7	P2 X P3 X P5	P4 X P5
8	P2 X P6	P2 X P6	P5 X P6	P3 X P4 X P7	P5 X P5 X P7	P1 X P5 X P6
9	P6 X P7 X P7	P5	P5 X P5 X P6	P2 X P6	P7 X P7 X P7	P1 X P3 X P5
10	P3 X P7	P6 X P7 X P7	P6 X P6 X P6	P1 X P5 X P5	P4 X P4 X P4	P5 X P5 X P7

Considering that avoiding unnecessary complications is one of the precepts of classical statistics, one may question the wisdom of using these additional product and cross-product terms. However, the extremely large sample size virtually assures that any insignificant predictors will be assigned very low regression coefficients and indeed this is the case. Thus, it is believed that the inclusion of these terms could be beneficial but not detrimental to the final prediction system. Further comments on statistical significance of the results is given in section 7.

4. RESULTS

A. Dependent Data

Information relating the performance of the ten-predictor equations is given in table 4. The reduction of variance, which is given by the

Table 4.--System performance on development data, 1900-1972. Predictand is change of maximum sustained wind speed. Errors are given in knots.

	Forecast period (h)					
	12	24	36	48	60	72
1. Number of cases	9259	7928	6785	5793	4945	4212
2. Reduction of variance (%)	40	42	43	46	48	52
3. Multiple corr. coef.	.63	.64	.65	.68	.69	.72
4. Standard error	6.2	10.3	13.5	15.7	17.6	18.6
5. Mean abs. error	4.2	7.4	10.1	11.9	13.5	14.4
6. Mean error (bias)	0	0	0	0	0	0

square of the multiple correlation coefficient times 100, increases with the longer period forecasts. This somewhat surprising result is very similar to the finding of Elsberry et al. (1974) in their development of regression equations for the Western North Pacific. It is related to the nature of the forecast problem in that the predictand standard error is increasing at a disproportionately higher rate than is the standard deviation of the predictand itself. The mean absolute error does not increase linearly with time. Again, this is similar to the Elsberry et al. (1974) findings that error per forecast hour decreases.

B. Independent Data

The ten-predictor equations were tested using the second data sub-set, those tropical cyclones in the period 1973 through 1977. Table 5 gives the results of this test.

Table 5.--System performance on independent data, 1973-1977. Predictand is change of maximum sustained wind speed. Errors are given in knots.

	Forecast period (h)					
	12	24	36	48	60	72
1. Number of cases						
4. Standard error						
5. Mean abs. error						
6. Mean error (bias)						

Comparison between table 5 and its dependent data counterpart, table 4, reveals the usual deterioration in performance between dependent and independent data. These differences are quite small, however. The non-zero biases in the independent data are also quite small and occur because the dependent and independent data have somewhat different statistical properties.

5. OTHER STRATIFICATIONS

A. Spatial Stratification Of The Data

Strategic stratification typically improves on the performance of a statistical model. An interesting hypothesis is appropriate at this point. A set of regression equations has been developed for the total basin. However, if one looks at a map of the basin (figure 1), several geographical regions in which one might statify data and develop equations similar to the ones for the total basin can be noted. Furthermore one might wish to divide the North Atlantic Ocean at the mean latitude of storm recurvature as was done by Elsberry et al. (1974). Therefore, six such statifications were made. These are termed the North Atlantic region, the Gulf of Mexico region, the Caribbean region, the Gulf of Mexico/Caribbean region, the North Atlantic region south of 30°N, and the North Atlantic region north of 30°N.

Ten-predictor equations were developed for each region in the same manner as for the total basin equations. Stratification obviously reduces sample size. However, as seen in table 6, the number of cases is still relatively large for development of the prediction equations.

Table 6.--Number of cases used to determine prediction equations, 1900-1972, for various spatial stratifications.

Forecast times	12	24	36	48	60	72
Total Basin	9259	7928	6785	5793	4945	4212
Atlantic Region	6679	5937	5251	4609	4022	3497
Gulf Region	1044	732	497	335	225	148
Caribbean Region	1546	1268	1046	856	705	573
Gulf Caribbean Region	2586	1996	1539	1189	928	720
Atlantic Region (South of 30°N)	3962	3744	3516	3254	2941	2632
Atlantic Region (North of 30°N)	2717	2193	1735	1355	1081	865

Appendix 1 gives the results of the test of these equations for the independent part of the data as well as the results using the total basin equations. In all the comparisons, except one, the total basin equations outperform the regional equations. The lone exception is the North Atlantic region north of 30°N for time periods 36 hours and beyond. Thus, the added complexity of a spatial stratification might be justified in this case. However, the decision was made to use the total basin equations until such time that additional operational test data are available.

B. Temporal Stratification Of The Data

Jarvinen and Caso (1978) indicate that before the beginning of organized reconnaissance during World War II, determination of storm intensities were based solely on ship and land observations. This suggests developing equations for the time periods before and after the establishment of hurricane reconnaissance. Allowing several years for the reconnaissance program to establish itself, one might wish to look at the time period 1946 through 1972 as well as 1900 through 1945. Therefore ten-predictor equations using total basin data were developed for both time periods. The equations were tested on the independent data

1973 through 1977. The statistical properties of the two sets of prediction equations are presented in appendix 2. Table 7 lists the mean absolute errors of the two sets of prediction equations that were generated from the independent data sample 1973 through 1977. Also shown are the mean absolute errors taken from table 5.

Table 7.--Homogeneous sample of mean absolute errors (knots) of intensity forecasts for three temporal stratifications of the total basin data. The forecast period is 1972-1977.

Stratification time period	Forecast period (h) 12	24	36	48	60	72
1. 1900-1945	5.4	9.1	11.6	14.2	15.1	17.3
2. 1946-1972	5.4	9.0	11.8	13.7	15.1	16.1
3. 1900-1972	5.4	8.7	11.5	13.4	14.7	15.7

Comparison of the results show that the first two stratifications produce approximately similar results. However, the combination of both time periods produces better forecasts except at the 12 hour period. There is an indication that the longer the period of record the better the forecast equations will be. This suggests redeveloping the regression equations using the total time period 1900 through 1977.

6. REAL TIME OFFICIAL FORECASTS VERSUS TOTAL BASIN EQUATIONS FORECASTS

Beginning in 1976, the real time official intensity forecasts were verified against the "best wind" profiles for each storm. These profiles were constructed from all available wind data at the end of each hurricane season.

Table 8 gives the combined results for 1976 and 1977. Note that, on the average, the forecaster does not know the initial intensity within approximately seven knots. The same cases, using real time operational input, were run using the total basin equations. These results are also shown in table 8. Comparison of the values show that, on the average, the statistical model does better for the short range forecasts while the forecaster performs better for the long range forecasts. This suggests that the forecaster is indeed showing some "skill" at the extended forecast periods, with this skill being derived from synoptic reasoning.

It is often instructive to determine how much better or worse the forecasts might be if both best wind and best track data were used (i.e. zero initial error). This cannot be done for the official forecasts but was accomplished for the statistical forecasts. The results are given in table 9.

Table 8.--Verification of the official and statistical maximum wind forecasts using a homogeneous sample for the period 1976 through 1977. Values are given in knots.

	Forecast period						
	Initial	12h	24h	36h	48h	60h	72h
Mean Error Official	1.7	1.6	1.8		-1.0		-2.2
Mean Error Statistical	1.7	.5	-1.3		-3.4		-3.2
Mean Abs. Error Official	6.6	9.6	12.8		15.7		14.4
Mean Abs. Error Statistical	6.6	9.4	12.0		16.1		16.0
Cases	199	199	169		124		87

Table 9.--Verification of the statistical maximum wind forecasts using best wind and track data for the time periods 1976 through 1977. Values in knots.

		Forecast period (h)					
	Initial	12	24	36	48	60	72
Mean Error	0	-.9	-1.6		-2.9		-.1
Mean Abs. Error	0	5.6	9.2		13.9		15.5
Cases	199	199	169		124		87

As one might expect, the "best everything" initial data leads to improved performance of the model. This stresses the need for the forecaster to determine the initial wind speed as carefully as possible as well as keeping an accurate wind speed profile.

7. TEST OF SIGNIFICANCE

As pointed out by Neumann et al. (1977) use of the classical F-test to determine the significance of regression equations generated by stepwise screening of predictors often leads to over estimates of the F-statistic. Therefore, to avoid possible pitfalls of the F-test that are associated with meteorological data and the regression procedure, it was decided to use the Monte Carlo significance test.

The Monte Carlo significance test was applied to the six total basin equations. An example of the process will be presented for the 12-hour prediction equation.

To establish a test statistic the 9259 predictor sets (i.e., each predictor set contains 119 predictors) were matched with 9259 randomly selected predictands. The same stepwise screening regression program, that was used to generate the original regression equations, was then initiated and run 100 times, each time using a different set of randomly chosen predictands but keeping the same set of predictors. The procedure yields 100 values of the multiple correlation coefficient ranging from a low of .043 to a high of .072. Figure 5 is the frequency distribution plot and a culmulative frequency distribution (cpf) plot of the 100 values of the multiple correlation coefficients. The actual

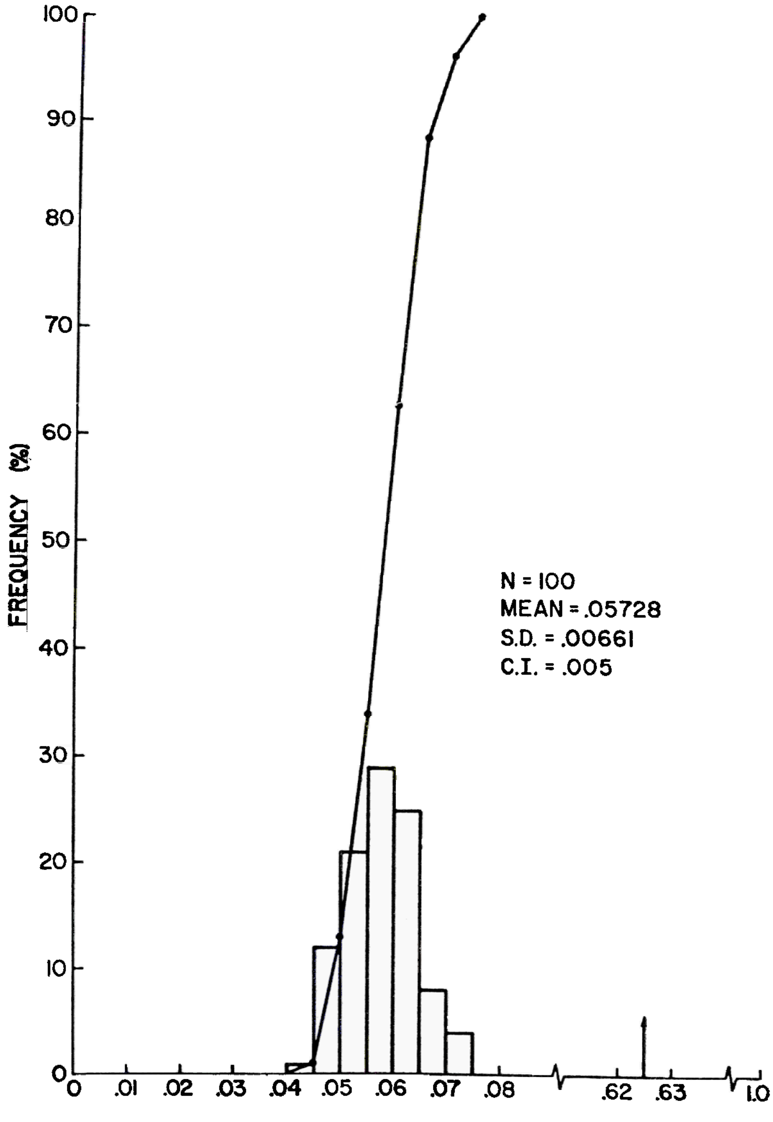


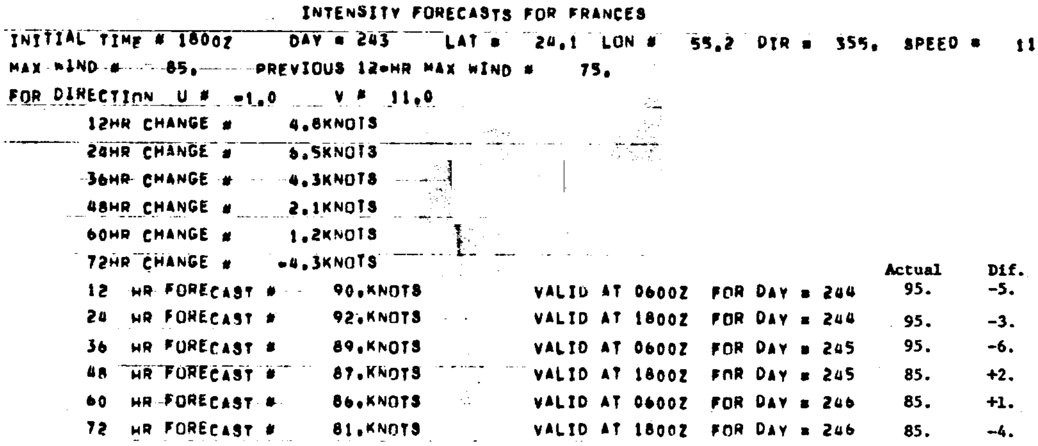
Figure 5. Frequency distribution and culmulative frequency distribution of the multiple correlation coefficients. S.D. = standard deviation. C.I. = class interval

multiple correlation coefficient is indicated by an arrow at .625. This value is an order of magnitude greater than the 99 percentile of the cpf plot. Thus, from these results one can say that the possibility of the correlation coefficient (.625) occurring by chance is negligible. Similar results were found for the other five equations. Such equations would be expected to perform well in an operational environment.

8. TWO EXAMPLES

A. Example 1

Figure 6 is a copy of the computer printout of a simulated real time operational forecast for hurricane Frances (1976). The seven primary predictors necessary for the regression equations are available in an operational time frame, and are listed at the top of the figure. All primary predictors except the previous 12-hour maximum wind speed are used in current operational statistical track models.



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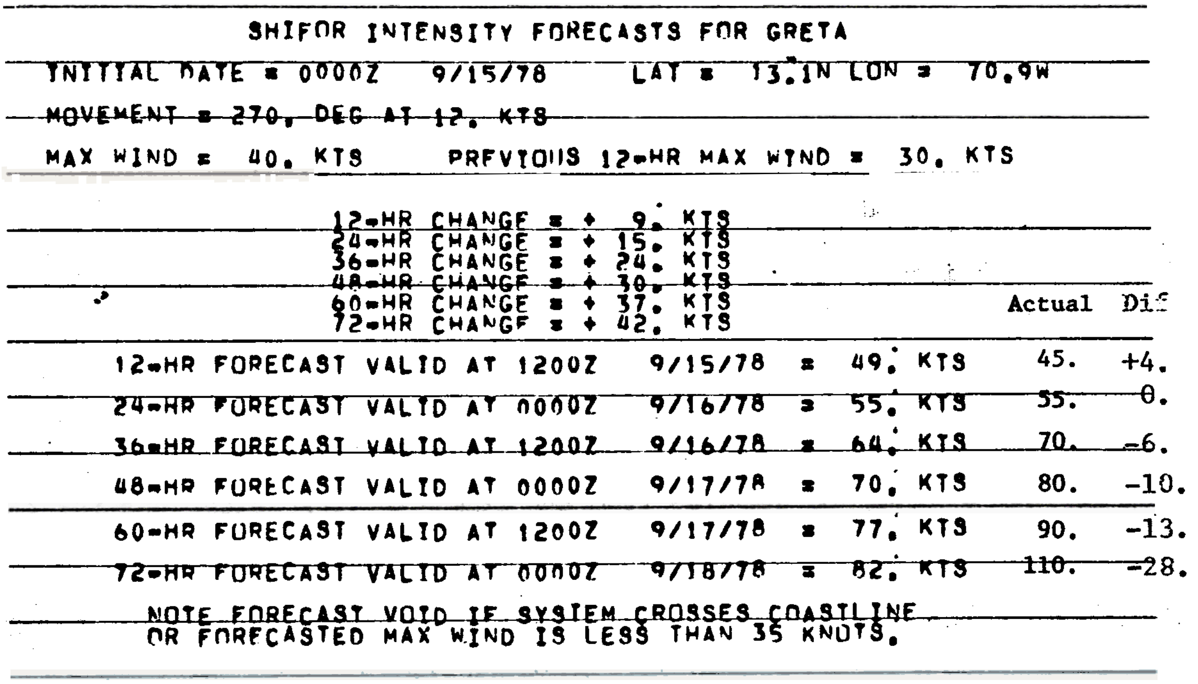
                                INTENSITY FORECASTS FOR FRANCES
INITIAL TIME # 1800Z       DAY = 243      LAT =   24.1  LON #   55.2  DIR =  355.  SPEED =    11.
MAX WIND #     85.     PREVIOUS 12-HR MAX WIND #     75.
FOR DIRECTION  U #  -1.0      V #  11.0
        12HR CHANGE #      4.8KNOTS
        24HR CHANGE #      6.5KNOTS
        36HR CHANGE #      4.3KNOTS
        48HR CHANGE #      2.1KNOTS
        60HR CHANGE #      1.2KNOTS
        72HR CHANGE #     -4.3KNOTS                                                 Actual    Dif.
        12  HR FORECAST #       90.KNOTS             VALID AT 0600Z  FOR DAY = 244   95.      -5.
        24  HR FORECAST #       92.KNOTS             VALID AT 1800Z  FOR DAY = 244   95.      -3.
        36  HR FORECAST #       89.KNOTS             VALID AT 0600Z  FOR DAY = 245   95.      -6.
        48  HR FORECAST #       87.KNOTS             VALID AT 1800Z  FOR DAY = 245   85.      +2.
        60  HR FORECAST #       86.KNOTS             VALID AT 0600Z  FOR DAY = 246   85.      +1.
        72  HR FORECAST #       81.KNOTS             VALID AT 1800Z  FOR DAY = 246   85.      -4.
```

Figure 6. Copy of the computer printout for simulated real time operational intensity forecasts for hurricane Frances (1976). Verification of the forecasts is given in the last two right hand columns. Values are in knots.

This particular case of hurricane Frances, in the process of recurvature, was selected to show that the model has the capability of forecasting non-linear intensity changes. The model forecasts an increase in intensity up to 24 hours and then a decrease thereafter out to 72 hours. This is similar to an intensity profile one would expect for a recurving storm. The actual intensity values, which were obtained after a post-season analysis of all the intensity data and rounded to the nearest five knots, are indicated in the lower right hand column. The differences of the forecasted minus the actual value are given in the last column under "Dif". Inspection of the results indicate that the model performed very well in this particular case.

B. Example 2

Figure 7 is a set of real time operational statistical intensity forecasts for tropical cyclone Greta (1978). This figure differs from figure 6 in that the seven primary predictors are printed in their original form as given by the forecaster. This particular example is instructive to review because it indicates the limitations of the model.



```
                 SHIFOR INTENSITY FORECASTS FOR GRETA
  INITIAL DATE = 0000Z    9/15/78      LAT =  13.1N LON =  70.9W
  MOVEMENT = 270. DEG AT 12. KTS
  MAX WIND =  40. KTS       PREVIOUS 12-HR MAX WIND =  30. KTS

                    12-HR CHANGE = +  9. KTS
                    24-HR CHANGE = + 15. KTS
                    36-HR CHANGE = + 24. KTS
                    48-HR CHANGE = + 30. KTS
                    60-HR CHANGE = + 37. KTS                          Actual   Dif
                    72-HR CHANGE = + 42. KTS

      12-HR FORECAST VALID AT 1200Z   9/15/78  =  49. KTS              45.    +4.
      24-HR FORECAST VALID AT 0000Z   9/16/78  =  55. KTS              55.     0.
      36-HR FORECAST VALID AT 1200Z   9/16/78  =  64. KTS              70.    -6.
      48-HR FORECAST VALID AT 0000Z   9/17/78  =  70. KTS              80.   -10.
      60-HR FORECAST VALID AT 1200Z   9/17/78  =  77. KTS              90.   -13.
      72-HR FORECAST VALID AT 0000Z   9/18/78  =  82. KTS             110.   -28.

         NOTE FORECAST VOID IF SYSTEM CROSSES COASTLINE
         OR FORECASTED MAX WIND IS LESS THAN 35 KNOTS.
```

Figure 7. Copy of the computer printout for real time operational intensity forecasts for tropical cyclone Greta (1978). Verification of the forecasts is given in the last two right hand columns. Values are in knots.

One might note in the seven primary predictors that the previous 12-hour maximum wind speed is equal to 30 knots. Although this is below the 35 knot limiting value used in the development of the prediction equations, such equations typically have the ability to support slight extrapolation.

From 0000 GMT 9/15/78, Greta continued to intensify slowly for 24 hours after which the storm began a moderate intensification for another 48 hours. As can be seen from figure 7, the statistical forecast errors were relatively small at 12 and 24 hours. The 36 hour forecast of 64 knots was too low but nevertheless would have suggested upgrading to hurricane intensity. Indeed, Greta was upgraded to a hurricane at this time based upon a 70 knot surface wind speed determined by aircraft reconnaissance. A deterioration of the forecast begins at this point and gets worse. However, as mentioned earlier this was a period of moderate intensification. As documented in figure 3b the actual change of 70 knots over 72 hours occurred less than one-percent of the time in the developmental data set. Therefore, the large error at 72 hours is not too surprising.

9. CONCLUSIONS

The standard deviations of the 12-, 24-, 36-, 48-, 60-, and 72-hour maximum tropical cyclone wind speed changes are indicative of the difficulty in forecasting these changes. The relatively small reduction of variances, 40 percent at 12 hours increasing to 52 percent at 72 hours, indicate that climatology and persistence can help only slightly in improving on our ability to forecast intensity changes. One must look elsewhere, presumably to environmental influences, to achieve additional reduction. Additional studies will follow.

Regression equations were derived for various spatial and temporal stratifications. Results from the spatial stratifications indicate that the total basin equations outperformed five other regional sets of equations. The lone exception was the set of equations derived for that part of the basin north of 30°N. However, the differences were noted only at 36- through 72-hours. A final decision on whether to include this set of equations will be made after additional operational data becomes available. Results from the temporal stratifications for the total basin show that the pre-reconnaissance era, 1900 through 1945, developed equations and reconnaissance era, 1946 through 1972, developed equations are not significantly different. However, the total era, 1900 through 1972, developed equations produced better results. This suggests redeveloping the total basin equations at the end of each tropical cyclone season to take advantage of this additional information.

Monte Carlo significance tests showed that the possibility of generating values of the multiple correlation coefficients, obtained in this study, by chance are negligible.

While the regression equation forecasts are somewhat better at 12- and 24-hours when compared to the official forecasts, the reverse is true at 48- and 72-hours. This suggests that the forecaster may be making better forecasts at the later time periods because of his use of synoptic reasoning.

It is hoped that this statistical intensity forecast model will provide a convenient benchmark upon which to base the skills of more sophisticated models as well as the official forecast of intensity changes.

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Comparison of the regionalized developed ten predictor equations and the total basin developed ten predictor equations. Verification is for tropical cyclones occurring in the time period 1973 through 1977. Values are in knots.

ATLANTIC REGION USING ATLANTIC DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	.05	-.13	.16	.20	.33	1.34
ABS. MEAN	5.12	8.29	11.22	13.01	14.80	16.45
STD. DEV.	6.98	10.90	14.15	16.56	18.30	19.64
CASES	459	394	337	284	235	193

GULF REGION USING GULF DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-8.18	-17.15	-33.10	-	-	
ABS. MEAN	10.81	20.31	34.77	-	-	
STD. DEV.	13.65	21.61	27.33	-	-	
CASES	27	15	6	-	-	

CARIBBEAN REGION USING CARIBBEAN DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-3.77	-10.21	-31.28	-	-	-
ABS. MEAN	5.52	12.58	31.96	-	-	-
STD. DEV.	7.40	12.83	17.61	-	-	-
CASES	17	11	5	-	-	-

GULF CARIBBEAN REGION USING GULF CARIBBEAN DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-5.77	-13.29	-32.31	-53.05	-	-
ABS. MEAN	8.60	17.49	33.44	53.05	-	-
STD. DEV.	11.81	19.68	24.08	12.33	-	-
CASES	44	26	11	5	-	-

SOUTH ATLANTIC REGION USING SOUTH ATLANTIC DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	.94	1.83	4.23	5.18	6.16	6.72
ABS. MEAN	5.37	9.41	12.22	13.57	14.63	15.34
STD. DEV.	7.15	11.88	14.71	16.18	16.93	17.71
CASES	166	154	145	133	120	108

NORTH ATLANTIC REGION USING NORTH ATLANTIC DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-.59	-1.16	-1.52	-2.30	-3.63	-6.38
ABS. MEAN	5.00	7.83	9.85	11.78	13.62	15.88
STD. DEV.	6.84	10.36	12.71	14.65	16.29	18.26
CASES	293	240	192	151	115	85

ATLANTIC REGION USING TOTAL BASIN DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-.05	-.10	.74	.49	1.82	2.12
ABS. MEAN	5.07	8.23	10.91	12.85	14.53	15.66
STD. DEV.	6.93	10.90	14.20	16.33	18.02	19.28
CASES	459	394	337	284	235	193

GULF REGION USING TOTAL BASIN DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-6.16	-14.19	-31.89	-	-	
ABS. MEAN	10.24	19.15	31.89	-	-	
STD. DEV.	13.30	21.30	25.13	-	-	
CASES	27	15	6	-	-	

CARIBBEAN REGION USING TOTAL BASIN DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-3.36	-10.09	-24.33	-	-	-
ABS. MEAN	5.38	11.81	25.76	-	-	-
STD. DEV.	7.23	11.06	15.32	-	-	-
CASES	17	11	5	-	-	-

GULF CARIBBEAN REGION USING TOTAL BASIN DERIVED EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-5.08	-12.46	-28.45	-44.61	-	-
ABS. MEAN	8.36	16.04	29.10	44.61	-	-
STD. DEV.	11.43	17.82	21.57	13.61	-	-
CASES	44	26	11	5	-	-

SOUTH ATLANTIC REGION USING TOTAL BASIN EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	0.71	1.90	3.08	4.21	5.71	6.25
ABS. MEAN	5.23	8.99	11.98	13.25	14.53	15.42
STD. DEV.	7.02	11.63	15.22	16.45	17.17	18.21
CASES	166	154	145	133	120	108

NORTH ATLANTIC REGION USING TOTAL BASIN EQUATIONS

FORECAST TIMES	12	24	36	48	60	72
MEAN	-.49	-1.38	-1.03	-2.79	-2.24	-3.13
ABS. MEAN	4.98	7.74	10.10	12.50	14.54	15.96
STD. DEV.	6.85	10.21	13.10	15.51	17.98	19.33
CASES	293	240	192	151	115	85

APPENDIX 2

TABLE 1. The 1900-1945 generated total basin equations system performance on independent data, change of the maximum sustained wind speed. Errors are given in knots. Time period 1972-1977

	Forecast Period (h)					
	12	24	36	48	60	72
Number of Cases	503	420	348	289	236	193
Standard Error	7.7	12.4	15.4	18.4	19.3	22.3
Mean Abs. Error	5.4	9.1	11.6	14.2	15.1	17.3
Mean Error (Bias)	-.5	-2.1	-1.6	-2.2	-2.1	-2.6

TABLE 2. The 1946-1972 generated total basin equations system performance on independent data, (1972-1977) change of the maximum sustained windspeed. Errors in knots.

	Forecast Period (h)					
	12	24	36	48	60	72
Number of Cases	503	420	348	289	236	193
Standard Error	7.6	12.0	15.1	17.2	18.4	19.2
Mean Abs. Error	5.4	9.0	11.8	13.7	15.1	16.1
Mean Error (Bias)	-.3	-.2	.6	1.9	-.1	2.2