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AN EXPERIMENT IN STATISTICAL PREDICTION OF TROPICAL CYCLONE INTENSITY CHANGE

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CONTENTS

LIST OF ABBREVIATIONS, INITIALS, AND ACRONYMS

ATOLL - Analysis of tropical oceanic lower layer; a National Hurricane Center objective analysis of the low-level wind field from ship, 1500 m pibal, 850 mb rawinsonde, and low level cloud track winds. The same analysis algorithm is used to prepare a 200 MB analysis from rawinsondes, aircraft reports, and upper level cloud track winds.

C - 2*sin(Y) (nondimensional Coriolis parameter).

CHIPS - Combined Hurricane Intensity Prediction System; a collective name for the models (CP, SY, and CO) described in this paper.

CO - Combined intensity change prediction model (CP with additional synoptic predictors)

CP - Climatology-persistence intensity change prediction model; uses initial position, intensity and motion of the storm, persistence of past intensity change, and forecast motion, SST, and land effects as predictors.

D - Julian day number.

DXF - zonal (eastward) forecast displacement of the storm during a particular forecast interval (refer to Section 1A for a definition of 'forecast interval').

DYF - same as DXF except for meridional (northward) forecast displacement.

DWP - past 12 h intensity change.

MSLP - minimum sea level pressure.

NMC - National Meteorological Center.

NHC - National Hurricane Center.

PCA - Point of closest approach to land; the point on a storm's path that is closest to land during a specific time interval.

SHIFOR - Statistical hurricane intensity forecast; a statistical model (Jarvinen and Neumann, 1979) using initial position, date, location, motion, and persistence of intensity change of a storm as predictors.

SF - forecast speed of storm motion from official forecast positions.

SST - Sea surface temperature (SST0 at initial location, SSTF at forecast location).

S0 - speed of storm motion over 12 h prior to initial time.

SY - Synoptic component of CHIPS; uses winds from the NHC ATOLL-200 MB package as predictors.

U - zonal motion of storm over past 12 h. If lower case, indicates zonal wind.

V - meridional motion of storm over past 12 h. If lower case, indicates meridional wind.

VT - tangential wind, counterclockwise positive.

W - initial intensity.

- SST cap predictor, given by (W-S0) - WSST(SST0), which is the difference between the initial relative intensity (defined in Section 1A) and the empirical maximum intensity associated with the climatological SST at the intial position.
- same as WS0 except evaluated for the forecast storm motion and climatological SST at the forecast position; (W-SF) - WSST(SSTF).

WSST(T)- empirical maximum intensity (maximum wind minus translation speed) at a climatological SST of T °C.
X - initial longitude (west negative).
Y - initial latitude (north positive).

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ABSTRACT

The development of a family of statistical models of tropical cyclone intensity change as a function of climatology, persistence, and synoptic variables is described. The climatological sea surface temperature (SST) distribution and the effects of proximity to land are explicitly included in the climatology-persistence (CP) model, which is developed from National Hurricane Center (NHC) best track data from 1962-1985. This model performs nearly as well as the current operational SHIFOR model over water and produces results consistent with the official forecast track over and near land.

Output from the CP model is used along with pre-selected predictors from lower- and upper-tropospheric wind analyses to produce synoptic (SY) and combined (CO) models. Synoptic predictors are statistically significant when used alone, but do not yield a significant improvement to the CP model. Suggestions are made regarding the direction of future attempts at intensity change prediction.

1. INTRODUCTION

Although meteorologists have often suggested relationships between the environment of tropical cyclones and their subsequent changes in intensity, there have been relatively few attempts to quantify these relationships as guidance for forecasters. At present, the National Hurricane Center (NHC) has three aids for intensity** prediction; SHIFOR (Jarvinen

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**The quantity actually predicted by these regression models is "intensity change" rather than "intensity"; the latter term is used for brevity.

and Neumann, 1979), SPIKE (Pike, 1985), and forecasts made from satellite imagery using the Dvorak (1984) method. Only SPIKE specifically includes environmental information (in the form of thicknesses from National Meteorological Center hemispheric analyses) and the additional skill beyond SHIFOR, though statistically significant, is small.

This attempt to develop improved intensity guidance for NHC is prompted by Merrill's (1985, 1988) description of specific environmental conditions thought to be associated with intensity changes, and the availability at NHC of a 10 year archive of locally produced lower- and upper-tropospheric wind analyses containing many supplementary observations.

In the remainder of this section current intensity prediction methods will be surveyed and the specific objectives of the current model presented.

A. Definitions

Forecast interval - the elapsed time from the initial conditions from which a forecast is made to the time at which the forecast is valid.

Intensity - A measure of the extreme meteorological conditions associated with a tropical cyclone (highest wind speed, lowest sea level pressure, etc.) Throughout this paper, "intensity" will refer to the post-analysis or "best track" maximum wind as archived at NHC (Jarvinen et. al., 1984), nominally the 1 minute surface wind (10 m elevation over water).

Relative intensity Intensity minus the speed of motion of the storm.

Storm - Tropical cyclone having an intensity of 17.5 m s^{-1} (34 kt) or more, therefore including tropical storms and hurricanes, but excluding tropical depressions.

B. Survey of guidance for intensity prediction

The simplest forecasting methods are those using intensity climatology (mean intensity or intensity change for different locations and times of year) and/or persistence. Tabulations of past intensity changes for specific regions can be used as a forecast aid as well as a research tool (Frank and Jordan, 1960). Refinements such as the addition of stratifications according to individual storm characteristics (i.e. initial motion; Michaels, 1973) can make the climatology still more useful. Riehl (1972) presents a climatology model of the weakening of typhoons after recurvature using statistical regression to relate intensity and latitude.

Intensity climatology can be generalized and automated for operational use by fitting regression equations for intensity or intensity change to functions of the position and Julian date. The past intensity change can be added to the mix of potential predictors as well to yield a "climatology-persistence" model. SHIFOR (Jarvinen and Neumann, 1979) is of this type and also uses as predictors the past 12 h motion of the cyclone (indirectly yielding information about the synoptic flow) and current intensity (which gives some measure of the initial character of the vortex).

SHIFOR can be used as a "benchmark" for intensity prediction (Steranka et. al., 1986); outperforming SHIFOR indicates that an aid (or forecaster) is able to make use of the current synoptic situation or vortex characteristics effectively. CLIPER, a climatology-persistence model for motion, is already used for indexing the skill of track models and official track forecasts (Neumann and Pelissier, 1981).

The logical step beyond the SHIFOR-type model has been to add additional information about the environmental flow (Arakawa, 1963; Elsberry et. al., 1974; Dropco, 1981; Cook, 1985; Pike, 1985) to produce a statistical synoptic model. Though synoptic and climatology-persistence predictors are both available for screening in all but Dropco (1981), the latter typically provide most of the reduction of variance. Pike (1985) conducted a search for those predictors which would make a statistically significant improvement to SHIFOR and was only able to find one, and it only improved the results in a certain range of latitudes. The statistical-synoptic approach has thus far proven more fruitful for track prediction than for intensity change, where the addition of synoptic information almost always improves the forecast, particularly at higher latitudes and longer forecast intervals (Neumann, et. al., 1972).

Numerical simulation and theoretical studies have highlighted the role of interactions between the vortex and moist processes in tropical cyclone development, as summarized in Anthes (1982) and Ooyama (1982). These effects are on sub-synoptic scales and cannot readily be measured with conventional observations. However, satellite imagery allows frequent sensing of some convective properties and aircraft can provide additional in situ measurements of the storm core, so different intensity prediction methods have grown up around these specialized data sources.

The method of Dvorak (1984) incorporates past intensities, typical development rates, and characteristics of the storm's satellite presentation, such as the amount, organization, and vigor of central and banding convection. This information is combined according to highly structured subjective rules to produce an intensity estimate. A 24 hour forecast can then be made by extrapolating the past development trend, with modifications according to additional satellite signatures within the tropical cyclone and in its environment. No definitive verification of the Dvorak method as a forecast aid exists, but a preliminary study by Lushine (1985) indicates that the technique is competitive with the available objective aids and the NHC official forecasts. Objective prediction techniques using satellite imagery (Steranka et. al., 1986) are still in the experimental stages.

Though prized as an analysis tool, little use has been made of aircraft data in intensity forecasting. Dunnavan (1981) describes a method of predicting the development of extremely deep typhoons by comparing the equivalent potential temperature (θ_e) measured in the eye with the minimum sea level pressure (MSLP); when both reach empirically determined critical values, subsequent deepening to 925 mb or less is forecast. The "concentric eye phenomenon" (Willoughby et. al., 1982) often observed in intense hurricanes has also been suggested as a forecast rule; appearance of a secondary wind maximum or eyewall at larger radii should indicate filling or arrested deepening for a period of time. Other rules based on asymmetric structures (Willoughby et. al., 1984) and/or convective vigor may also become apparent as a "library" of research flights is amassed, but no systematic means of intensity change prediction using aircraft measurements currently exists for use at NHC.

C. Objectives

The operational objectives of this research are to develop an intensity prediction model which can be activated and produce reasonable results for any storm in the NHC area of responsibility (including those proximate to or over land), using only data of a type and form routinely available in real time, while making maximum use of SST climatology and current synoptic information.

This model is also intended to test the hypothesized environmental influences proposed by Merrill (1988); 1) climatological SST imposes a clearly defined upper bound on intensity, 2) increased vertical shear of the environmental flow acts to inhibit intensification, and 3) constriction of the storm outflow, as indicated by strongly anticyclonic tangential winds in the upper troposphere, is associated with the cessation of intensification.

2. MODEL DESIGN

The new family of models is called CHIPS - combined hurricane intensity prediction system, and consists of a climatology-persistence component (CP), a component using synoptic data alone (SY), and a combined model (CO), consisting at present of CP with additional synoptic predictors which might improve its performance. As satellite or aircraft-based predictors are defined, they too can be incorporated into the flexible internal structure of CO. In order to meet the operational and scientific objectives stated above, the model incorporates the following features:

1) The intensity-dependent effects of proximity to minor, major, and elevated terrain are modeled statistically and explicitly incorporated as predictors in CP.

2) The predicted storm motion is included as a predictor pair using "perfect-prog" methodology. CP is developed using observed displacements and run operationally using official forecast tracks. Intensity forecasts are therefore consistent with the official forecast track.

3) Climatological SST distributions are included explicitly, using a capping function developed from the dependent data.

4). Vertical shear and tangential flow at 200 mb are explicitly made available as predictors for SY and CO.

3. DEPENDENT DATA SELECTION

A. Data sources

Development of CP and SY requires records of intensity changes and the associated tropical cyclone tracks, a climatology of SST, digitized geography for the land effects, and analyses of the environmental flow.

Records of track and intensity (location and maximum wind) back to 1876 are available on the NHC best track archive (Jarvinen, et. al., 1984). Reynolds (1982) has prepared a series of monthly means of SST on a two-degree grid for the entire globe using surface marine observations prior to 1976 archived by the National Climate Center. The coastlines (and 200 m elevation contour) were manually digitized for the land areas bordering the Atlantic basin, with greater resolution for those land masses frequently affecting tropical cyclones.

Potential sources of synoptic data available at NHC are NMC northern hemisphere geopotential height analyses since 1961 and ATOLL and 200 mb analyses since 1975. The former data were used by Pike (1985) with only limited success, so the ATOLL-200 mb set, which contains locally generated satellite cloud motions as well as aircraft, ships, and rawindonde observations, is used for synoptic data for this study. It is felt that the NHC 200 mb analysis gives the best operational representation of the important outflow layer structure available, and the raw data used to produce it (for 1977-1983) were used by Merrill (1988) to study environmental influences on intensity change.

Reconnaissance aircraft reports and satellite imagery are not used as sources of predictors in this study although both probably contain useful information. The former are not routinely available and a scheme depending on them would therefore be somewhat inflexible, and building a suitable digitized archive of satellite imagery for a sufficiently large and diverse sample of tropical cyclones is felt to be beyond the scope of the current project.

B. Choice of period of development data

Selection of dependent data is a critical step in the development of stepwise screening regression models, particularly for intensity prediction for which the data sources and quality vary so much over the total period of record. Variability found in a larger sample is desireable so long as it is real. However, variability in observation quality or archiving procedures must be controlled carefully, and this may mean excluding part of the sample before beginning.

Though intensities are nominally available for all storms since 1876, many milestones in observing systems have been passed since then. Reconnaissance aircraft were introduced in the mid 1940's and Doppler wind instrumentation installed in the late 1950's (Fuller, 1986). Weather satellites were introduced in the early 1960's and continuous monitoring from geostationary spacecraft began in the late 1970's. Methods of estimating intensity from the imagery have undergone many changes, too.

Changes in archive quality are harder to anticipate. The NHC best track file has been updated on a yearly basis only since the mid 1970's; earlier years are a reconstruction from a variety of sources and records. The storm tracks have been widely disseminated and used for many purposes and have undergone several revisions as errors are located and additional primary source material located. However, the intensity records have received much less scrutiny. It is therefore possible that fluctuations in data quality due to changes in the archiving process might also be present.

Since 1974 the over-water intensity records are based on a systematic annual postanalysis of aircraft reconnaissance (with instrumentation not unlike that currently in use) and satellite coverage from geostationary spacecraft with intensity estimates based on some form of the Dvorak (1984) method. The period 1974-1985 is therefore considered to be representative of current conditions. Earlier years are included as long as they are not inconsistent with 1974-1985; the measure of consistency adopted here is the sea surface temperature (SST) capping function (discussed in detail in the next section) derived for the period 1974-1985. The capping function is exceeded in individual cases about one percent of the time for 1974-1985. This "failure rate" remains at or below one percent for the period 1962-1973, and then jumps sharply to about ten percent for 1955-1961. It is thought that such an abrupt failure is due to a change in the archive quality, so the period prior to 1962 is rejected and 1962-1985 adopted as the development sample for the CP model.

The choice of a period of record for the synoptic data drawn from the ATOLL-200 mb package is quite straightforward since these analyses are only archived since 1975, within the period of CP data homogeneity. The SY and CO models are therefore developed using the full ATOLL archive period 1975-1985.

4. MODEL DEVELOPMENT

A. Climatology-persistence conponent

As described in section 2, the CP model contains explicit representation of land proximity and SST effects on intensity. These effects are described below.

1. Land effects

Previous studies of the influence of land on tropical cyclones are the numerical simulations of Bender et. al., (1985), an empirical filling rate for hurricanes moving inland along the U. S. Gulf and Atlantic coasts (Malkin, 1959), some geographically localized rules for Pacific typhoons (Brand and Blelloch, 1972, 1973), and the extensive statistical study of land and SST effects on typhoons of Nyoumura and Yamashita (1984). For forecasting purposes, a general empirical representation of land effects is needed if the model is to work under all conditions. It is generally thought that 1) tropical cyclones begin to "feel" the coast before their center actually reaches it, 2) rough terrain and large land masses have a greater effect, and 3) intense tropical cyclones decay faster than weaker ones. These ideas are all incorporated in the development of the land effects function.

Coastlines are represented as a series of line segments, with land masses classified as "major" or "minor" based on area. Trinidad is considered to be the smallest major body of land in the Atlantic basin. Mountainous terrain is represented by digitizing the 200 m contour (Bartholomew, 1977), which provides a convenient separation between flat and mountainous regions. Most Atlantic land areas which exceed 200 m elevation are actually much higher.

Since the CP forecast intervals are multiples of 12 h, the land effects function is derived for 12 h intensity changes. The "distance to land" is defined by the distance at the point of closest approach (PCA) in a 12 h period, measured at 3 h intervals. The land effects apparent in the dependent data are shown in Fig. 1. Note that the median (0.50) intensity change is near zero beyond 50-100 km and decreases linearly with distance for storms nearer the coast. To simulate this behavior in the model, the land effects function is selected from a family of "finite element" predictors, shown schematically in Fig. 2. Finite elements with break points at 50 km increments from -50 km to 400 km (50-200 km for minor land areas) from the coast (or 200 m contour for mountains) for major, minor, and mountainous land areas were made available as predictors, both "as is" and multiplied by the intensity at the beginning of the 12 h period. The distance at which land effects begin is determined by the function(s) selected, and the magnitude of the effect by the coefficients assigned by the regression analysis.

The first three terms selected explained 23, 4, and 0.4 percent of the variance respectively. The first two finite element forms selected have break points at a=100 km (E_1) and a=200 km (E_2). Land effects functions using either one or both terms are given by

$$LE_1 = 1.25089 + 0.1223226 * E_1, \qquad \text{and}$$

$$LE_2 = 0.881416 + 0.2118759 * E_1 - 2.4238561 * E_2.$$

The leading constant is the "open ocean" mean 12 h intensity change (PCA beyond 100 km and 200 km respectively). The first term (E_1) indicates a filling tendency within 100 km of the coast as expected, while E_2 indicates intensification within 200 km of land. CP models were developed using both one and

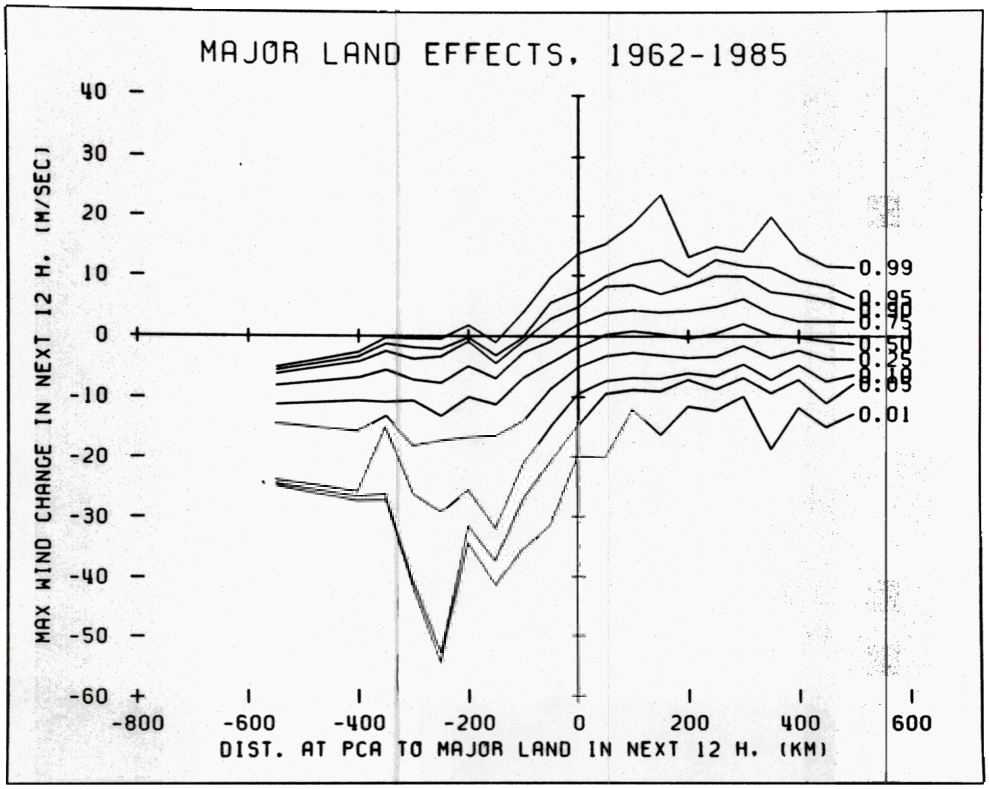


Fig. 1. Distribution of intensity changes in a 12 h period as a function of the distance to land at point of closest approach (PCA). Lines are percentiles of (top to bottom) 99, 95, 90, 75, 50, 25, 10, 5, and 1.

two term land effects and although the latter gave superior results on dependent data it is also overly sensitive to errors in the forecast track when used operationally. The operational CP model therefore uses a one term land effect.

After completion of this research, the author was made aware of of Nyoumura and Yamashita's (1984) study of land and SST effects on 24 h MSLP changes of western North Pacific storms. Their predictors are averages of SST and percent land coverage of a 4° latitude-longitude region centered on the storm for the past 24 h at 6 h intervals.

The Nyoumura and Yamashita method also indicates filling as the storm becomes more involved with land but a direct comparison is impossible. During land effects development, average distances to land were found to give inferior results to PCA distances, but the areal coverage method of Nyoumura and Yamashita was never considered. A direct comparison on identical data would be necessary to choose the superior method but would be worthwhile, considering the importance of overland filling rates in forecasting and planning.

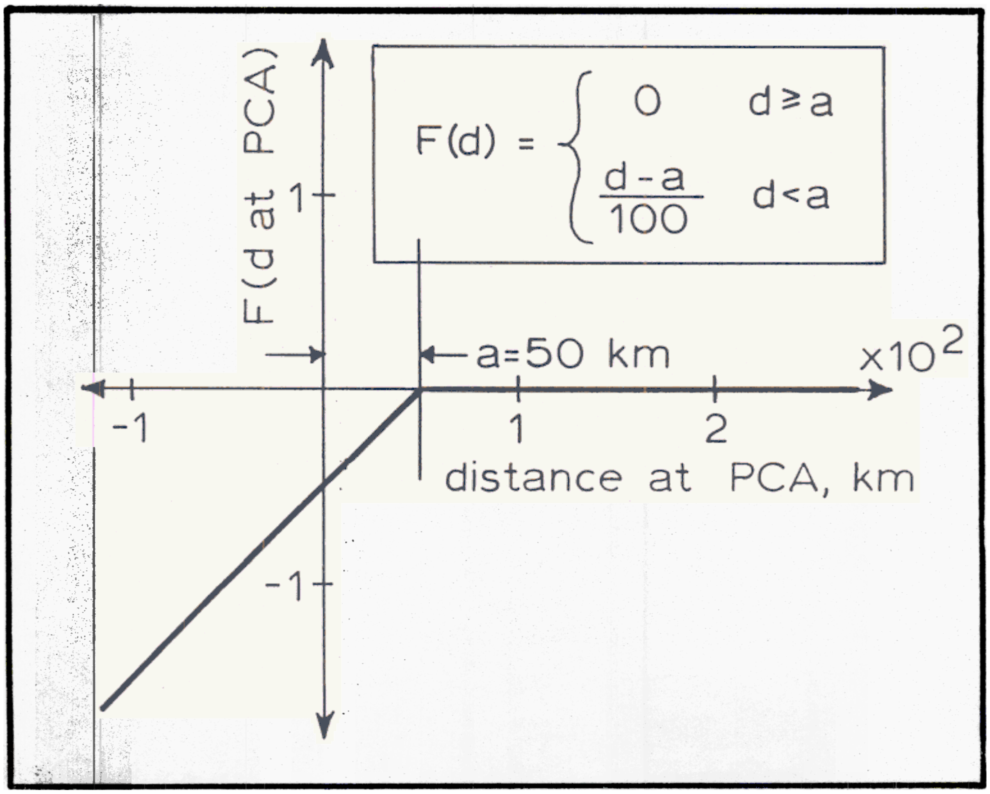


Fig. 2. Schematic of finite element predictors used to model land effects. The value of "a" determines the distance at which the land effect begins.

2. Sea surface temperature cap

Empirical studies by Miller (1958) and Merrill (1988) and theoretical results of Emanuel (1986) imply that SST specifies an upper bound on tropical cyclone intensity. The SST capping function is developed for the period 1974-1985 (Fig. 3) by tabulating maximum winds by 0.5 degree climatological (Reynolds, 1982) SST classes and computing the 99th percentile (Fig. 4). A smoother relationship results if relative intensities are used, since many of the extreme wind speeds found at high latitudes were associated with rapidly moving storms.

The reason for treating SST as a capping function rather than as a direct predictor is evident from Fig. 4. Compare the top three curves (90th percentile and greater intensity) which increase sharply above 27°C with the median (50th percentile) which is nearly uniform above 25°C. Knowing the climatological SST reveals little about the intensity of the average storm but much about the extreme intensity likely to occur.

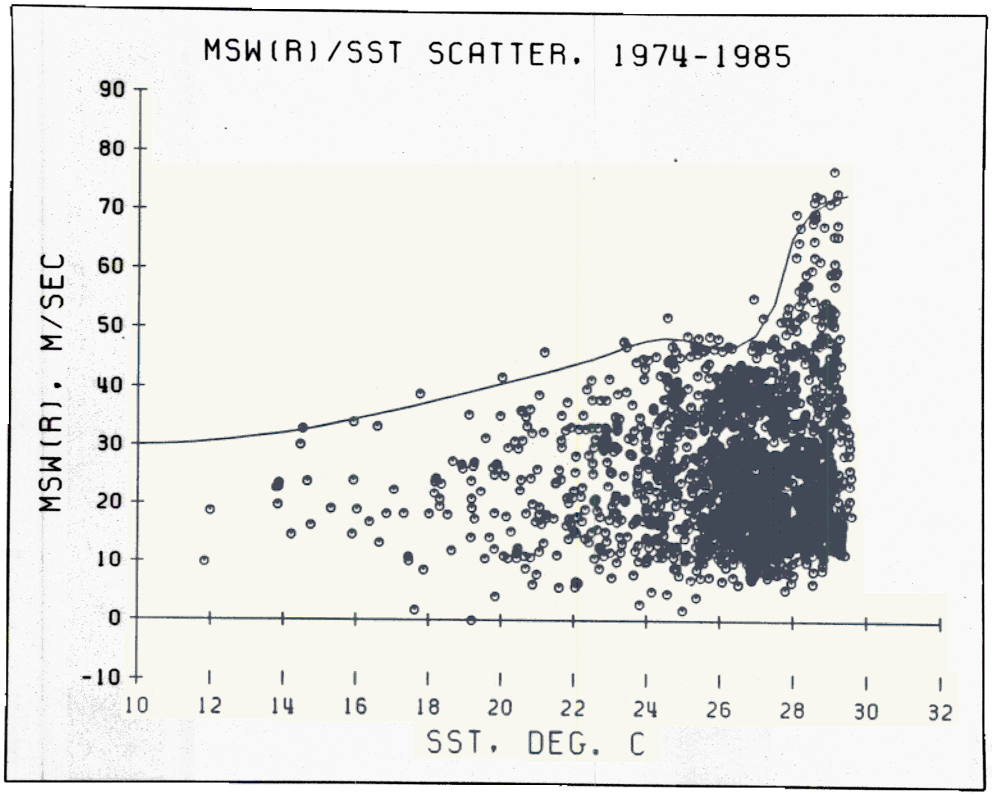


Fig. 3. Scatter plot of relative intensity versus climatological sea surface temperature. The SST capping function based on the 99th percentile (see Fig. 4) is superimposed.

The most interesting feature of the SST capping function is the sharp increase of peak intensities between 27.0° and 28.0°C. A more uniform increase would be expected based on the conclusions of Miller (1958) and Emanuel (1986). Holliday and Thompson (1979) suggest that 28.5°C is the minimum SST necessary for rapid deepening (42 mb or more in 24 h) of Pacific typhoons, and they also note that many of the more intense typhoons undergo rapid deepening. The results of Nyoumura and Yamashita (1984) as interpreted by Black (1986) also indicate a greater sensitivity of mean 24 h MSLP changes to SST from 28° to 29° than for any other 1° C range.

Another feature of note is the large number of hurricanes occurring at climatological SSTs below 26.5°C, which is frequently quoted as the minimum for hurricane formation (Palmen, 1948). Their numbers do not diminish appreciably even when the condition that the intensity be increasing over the past 12 h is imposed. It could be that these storms all occur in instances of warm local SST anomaly, but a case by case review would be necessary to confirm this. SST effects are made explicit in CP by including differences between the current

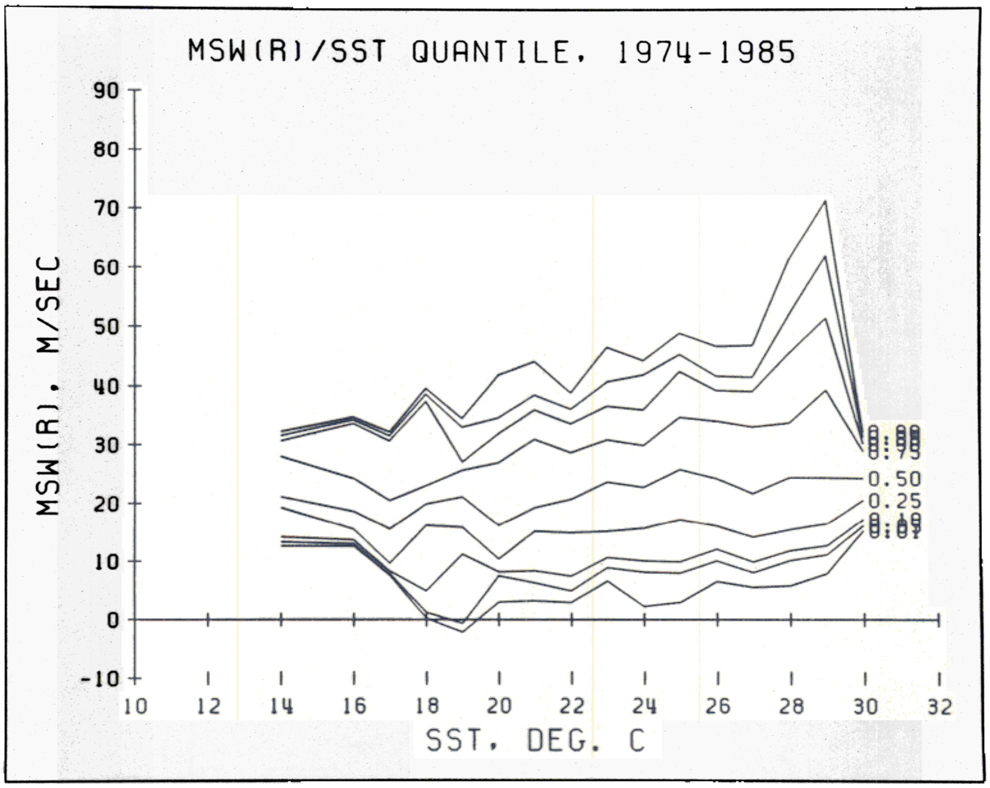


Fig. 4. Percentiles (values as in Fig. 1) fitted to the intensity-SST data shown in Fig. 3. The 30°C class (29.5°-30.5°) contains very few observations and is probably not representative of the extreme intensities possible.

relative intensity and the SST capping intensity for the current (and forecast) positions as predictors. All other conditions being equal, storms with intensities near or at the SST cap would be expected to intensify less than those well below it. The SST capping function is also used to assess data consistency by determining its failure rate for data prior to 1974, as described in section 3B).

3. Other climatological predictors

In addition to land effects and SST capping, the following predictors are also made available to the screening regression for CP; initial intensity, Julian day number, initial latitude and longitude, past 12 h zonal and meridional motion, future zonal and meridional displacements over the next 12, 24, 48, and 72 h, and observed intensity change over the past 12 h.

4. Model structure and regression

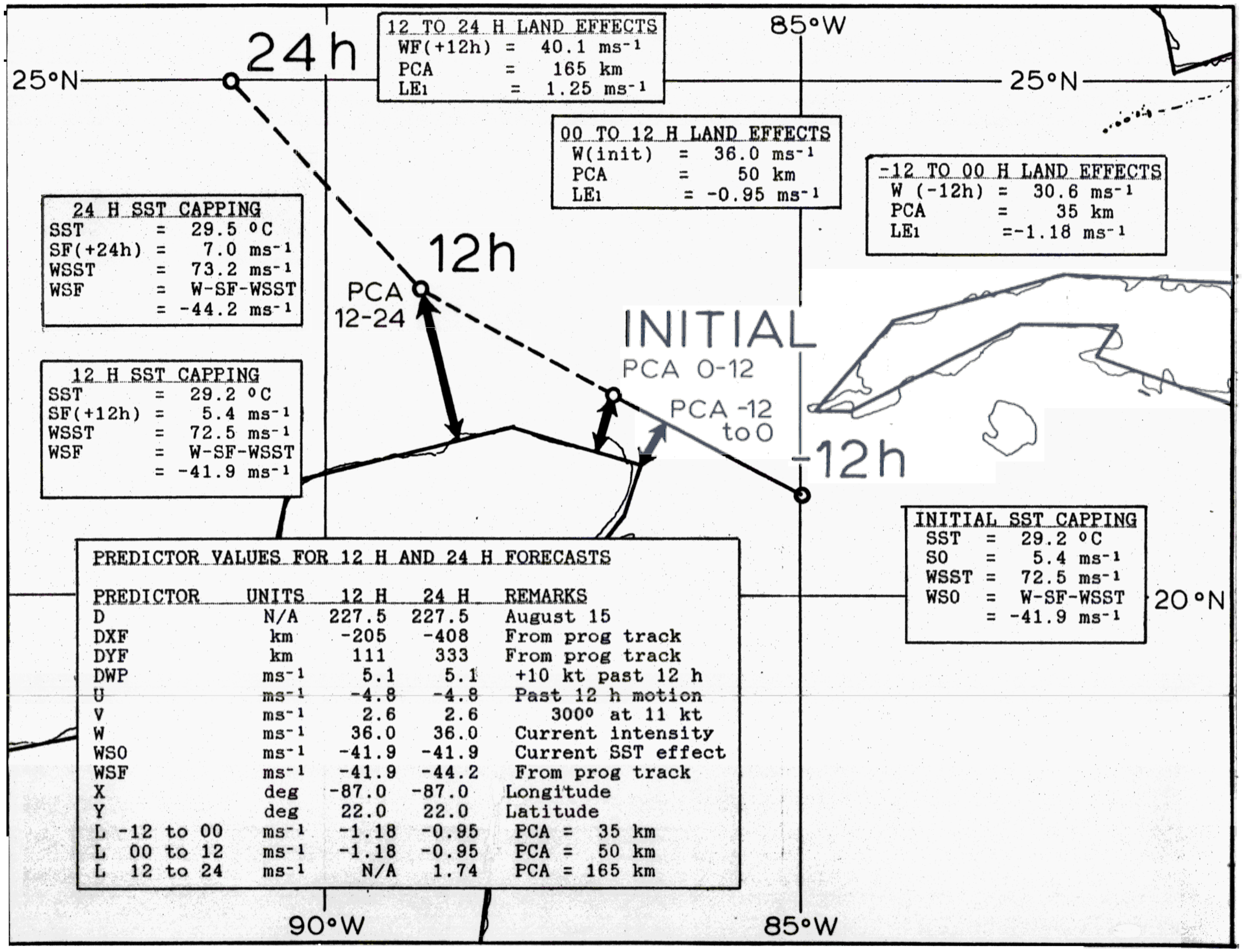
Screening regression for CP begins with the equation for 12 h intensity change. All initial value predictors are available, plus the past 12 h change of intensity and the past 12 h land effects, evaluated with the observed intensity from 12 h ago. "Perfect-prog" predictors for the 12 h forecast interval are also included; zonal and meridional displacements from the intial position to the observed position 12 h later, current relative intensity minus the SST capping function evaluated at the 12 h position, and the land effects associated with the next 12 h of the track. There are thus 13 first-order predictors available. Fig. 5 shows an example of the predictors.

Nonlinear effects are included by adding the cross products of all predictors except land effects for a total of 79 potential predictors. From these 79 predictors, those which yield a contribution to the total reduction of variance significant at the 95 percent level (using the "equivalent F" test described in Appendix A) are included in the preliminary 12 h forecast equation.

The 24 h forecast equation is developed similarly, except; 1) "perfect-prog" terms now involve the 24 h future position, and 2) an additional land effect, based on the cyclone track from 12-24 h, is now available as well as the -12 to 0 and 0 to 12 h land effects (Fig. 5 shows an example). To avoid overweighting the future land effects, the 12 h forecast intensity for each case (based on the preliminary 12 h forecast equation already developed) is used instead of the observed intensity to evaluate the land effects.

Screening is then continued for 36-72 h in sequence, with each screening regression being made against initial conditions and "perfect-prog" terms for the nearest official forecast time (48 h and 72 h positions and 0-48 h and 0-72 h displacements are used for the 36 h and 60 h intensity forecasts, respectively). Land effects are evaluated using forecast intensities and the perfect-prog track.

Once these preliminary predictor selections are made for all time periods, those predictors which either make a significant contribution at most forecast intervals or a dominant contribution at one or more intervals are included in the final predictor set. These subjective judgments are made so that the operational prediction equations will have the same predictors (though with different coefficients) at each forecast interval, minimizing the irregularity in the forecast intensity trend. Table 1 shows the preliminary predictors and their associated reductions of variance at each interval, and the predictors included in the final forecast equations.



12 TO 24 H LAND EFFECTS
WF(+12h) = 40.1 ms^{-1}
PCA = 165 km
LE_1 = 1.25 ms^{-1}

00 TO 12 H LAND EFFECTS
W(init) = 36.0 ms^{-1}
PCA = 50 km
LE_1 = -0.95 ms^{-1}

-12 TO 00 H LAND EFFECTS
W (-12h) = 30.6 ms^{-1}
PCA = 35 km
LE_1 =-1.18 ms^{-1}

24 H SST CAPPING
SST = 29.5 °C
SF(+24h) = 7.0 ms^{-1}
WSST = 73.2 ms^{-1}
WSF = W-SF-WSST
= -44.2 ms^{-1}

12 H SST CAPPING
SST = 29.2 °C
SF(+12h) = 5.4 ms^{-1}
WSST = 72.5 ms^{-1}
WSF = W-SF-WSST
= -41.9 ms^{-1}

INITIAL SST CAPPING
SST = 29.2 °C
SO = 5.4 ms^{-1}
WSST = 72.5 ms^{-1}
WSO = W-SF-WSST
= -41.9 ms^{-1}

PREDICTOR VALUES FOR 12 H AND 24 H FORECASTS

PREDICTOR	UNITS	12 H	24 H	REMARKS
D	N/A	227.5	227.5	August 15
DXF	km	-205	-408	From prog track
DYF	km	111	333	From prog track
DWP	ms^{-1}	5.1	5.1	+10 kt past 12 h
U	ms^{-1}	-4.8	-4.8	Past 12 h motion
V	ms^{-1}	2.6	2.6	300° at 11 kt
W	ms^{-1}	36.0	36.0	Current intensity
WSO	ms^{-1}	-41.9	-41.9	Current SST effect
WSF	ms^{-1}	-41.9	-44.2	From prog track
X	deg	-87.0	-87.0	Longitude
Y	deg	22.0	22.0	Latitude
L -12 to 00	ms^{-1}	-1.18	-0.95	PCA = 35 km
L 00 to 12	ms^{-1}	-1.18	-0.95	PCA = 50 km
L 12 to 24	ms^{-1}	N/A	1.74	PCA = 165 km

Fig. 5. Example of predictor calculations for a 12 h and 24 h forecast interval. Current intensity is 36.0 ms^{-1} (65 kt) and 12 h old intensity is 30.6 ms^{-1} (55 kt). "From prog track" refers to perfect prog (best track) information during model development and official forecast during operational application.

Table 1. Preliminary and final predictor selections for climatology-persistence (CP) model. The order of selection (in parentheses) and the percent of variance explained by each predictor are shown for each forecast interval. The predictors included in the final equations are noted at right.

Predictor	Forecast Interval						Kept ?
	12 h	24 h	36 h	48 h	60 h	72 h	
L -12-00	2.9 (4)	1.7 (11)	0.7 (8)	1.2 (8)	0.8 (11)		C
L 00-12	26.6 (1)	0.5 (10)	0.5 (9)				C
L 12-24		28.0 (1)	27.8 (1)	0.9 (7)	1.0 (7)		C
L 24-36			1.9 (4)	26.5 (1)		1.7 (5)	C
L 36-48				1.1 (6)	6.7 (2)		C
L 48-60					0.7 (10)	5.8 (2)	C
L 60-72						2.1 (4)	C
WSO			13.1 (2)	15.1 (2)			Y
W*X					25.4 (1)	28.8 (1)	Y
W*Y	1.0 (5)						Y
W*U	0.5 (8)	0.7 (7)			0.9 (9)	1.2 (9)	Y
W*V	1.2 (7)	1.6 (5)	1.9 (6)	1.6 (5)	2.0 (6)	1.4 (6)	Y
W*WSO	6.9 (2)	10.1 (2)			10.1 (3)	8.2 (3)	Y
W*WSF			1.5 (7)	0.7 (10)			
DN*V	0.4 (9)	1.0 (8)					Y
DN*DWP	0.5 (10)						
X*DYF	0.3 (6)	0.3 (6)	1.3 (5)	0.8 (9)	0.9 (12)		Y
Y*WSO					1.2 (8)	1.3 (8)	Y
Y*WSF		0.6 (9)					
DWP*WSF	3.9 (3)	4.6 (3)	3.6 (3)	3.6 (3)	2.2 (4)	1.3 (7)	Y
DYF*WSO	0.3 (11)						
DYF*WSF		1.7 (4)		1.4 (7)	1.6 (5)	1.8 (4)	Y
TOTAL	45.1	51.2	52.3	52.8	53.6	51.5	

Y = Predictor included in final forecast equations for all intervals
C = Predictor conditionally accepted and only included if actually selected as significant for that interval (applies to land effects only)

5. Results

Inspection of Table 1 reveals several interesting results. Land effects dominate the model out through 48 h, afterwards the term W*X (predictors are defined in the List of Abbreviations, Initials, and Acronyms) is selected first. This seemingly artifical transition arises because longitude is correlated with proximity to land. The inclusion of initial intensity in the term duplicates the intensity dependence of land effects. Longitude and land proximity are also correlated with SST; the warmest water found in the western part of the basin, particularly in the Caribbean Sea and Gulf of Mexico.

SST terms (W*WSO and WSO) are also selected early in the screening. Intensification is favored for systems which are already relatively intense and thus well-organized, but are still well below the SST cap. SST also weights the only persistence term selected (DWP*WSF), but the predictive value of

Table 2. Comparison of CP and SHIFOR performance on the CP development data (best tracks 1962-1985). SHIFOR dependent data is 1900-1980. N denotes sample size, BIAS the arithmetic mean error, ABS the mean absolute error, and RMS the root mean square error. CP results are the top number in each row.

Quantity		Forecast Interval					
		12 h	24 h	36 h	48 h	60 h	72 h
Cases more than 55 km from land throughout forecast interval							
N		2952	2567	2100	1929	1578	1464
BIAS	CP	-0.07	-0.19	-0.34	-0.39	-0.49	-0.38
	SH	0.09	-0.18	-0.50	-1.47	-2.05	-3.38
ABS	CP	3.22	5.08	6.40	7.42	7.98	8.38
	SH	3.18	5.22	6.76	7.95	8.70	9.38
RMS	CP	4.41	6.69	8.37	9.68	10.46	10.95
	SH	4.42	6.87	8.78	10.22	11.20	11.98
Cases less than 55 km from land at some time during the forecast interval							
N		774	852	784	846	727	748
BIAS	CP	0.27	56	0.90	0.	1.06	0.74
	SH	-4.10	69	-7.38	-9.	-9.61	-11.82
ABS	CP	4.49	02	6.78	7.	7.74	8.71
	SH	6.59	69	12.59	14.	14.70	16.31
RMS	CP	6.03	79	8.65	9.	9.85	10.92
	SH	14.77	10	16.06	15.	15.27	15.34

persistence is relatively small. Although the total variance explained by the equations ranges from 45 percent at 12 h to 55 percent at 48 h, this persistence term contributes less than 5 percent at any one interval.

Table 2 compares the performance of CP and SHIFOR on the CP dependent data. This is not a rigorous dependent data test since the SHIFOR dependent data are from 1900-1980, but it does illustrate that CP is clearly superior to SHIFOR only near or over land (cases within 55 km of land were excluded from SHIFOR development). Away from land the models' performances are similar; apparently third-order terms involving latitude, longitude, and Julian date are able to approximate SST effects. Third-order combinations of some CP predictors were also made available in a separate run, and yielded no additional skill. These results also support the finding of Jarvinen and Neumann (1979) that the use of pre-reconnaissance cases for SHIFOR development did not degrade its performance and may actually help the model by increasing the sample size.

B. Synoptic component

1. Dependent data

The 1975-1985 period is used for development of the synoptic (SY) and combined (CO) models. The former includes land effects for the future track (but evaluated with the current intensity at all intervals) while the latter includes the dependent data prediction from CP as a predictor. SY will identify the synoptic predictors which are directly related to intensity change, while CO will locate those (not necessarily the same) which make the greatest improvement upon a climatology-persistence forecast. For comparison, a CO-type model was also developed using output from SHIFOR for the climatology-persistence predictor.

2. Pre-selection of predictors

Each dependent data record consists of ATOLL and 200 mb winds on a 35 by 80 Mercator grid covering the Atlantic basin with a spacing (at Equator) of 1.5°, for a total of 5600 wind components (u and v). With only a few hundred cases, the predictor pool must be reduced considerably. Synoptic information is considered only in the near environment (within 1000 km of the center) to minimize the number of cases excluded because when some predictor locations fall outside the archive grid (which ends at 45°N). A further reduction was made by projecting the gridded wind components onto storm-centered cylindrical coordinates and performing a Fourier transform in azimuth, and retaining only the symmetric and wavenumber-1 components. The synoptic flow is then represented by 3 Fourier amplitudes per wind component at 2 levels and 5 radii, reducing the total predictor mix to 60 variables. Appendix B describes the synoptic predictors in greater detail.

"Custom" predictors based directly on the environmental interaction factors of Merrill (1988) were also included. The first of these is vertical shear. Since the environmental winds are computed relative to the storm motion, the symmetric U and V at 200 mb are approximations to the shear. However, subjective forecasting rules of Simpson (1971) and Hebert (1978) indicate that storms are more sensitive to vertical shear at low latitudes so an additional shear predictor, the symmetric 200 mb relative zonal wind divided by a nondimensional Coriolis parameter C=2*sin(Y) is made available.

The hypothesis of Merrill (1988) that intensification is curtailed by accumulation of heat in the upper troposphere is included indirectly in the form of tangential wind terms VT*VT and C*VT, which are proportional to the tangential wind terms in the cylindrical gradient wind equation.

Initial screening for synoptic predictor selection was performed with all cases whether over land or not. The predictors so selected were inconsistent from one forecast interval to the next and therefore diffficult to interpret. It was thought that these predictors might be artificial attempts to improve the model fit for the overland cases, so another screening was made with the dependent data restricted to those cases at least 100 km from land throughout the forecast interval. With this restriction the predictors selected are stable and easy to interpret. The land proximity was then reduced in 25 km steps as long as the selected predictors remained consistent from one run to the next, and a cutoff of 0 km found to be the minimum which still yielded consistent results. Unlike CP, the SY and CO models are therefore "tuned" to overwater cases.

3. Results

Table 3 shows the predictor selections for the SY model. Note that because of the restrictions on overland cases the land effects term, though active within 100 km of land, is no longer selected. Of the synoptic predictors, U2-600 (representing the average vertical shear at 600 km radius around the storm) is selected first at all time periods, with the tangential wind term FVT0-10 selected next. These selections tend to confirm the environmental influence hypotheses of Merrill (1988).

C. Combined model screening and results

Although significant when used alone in the SY model, screening for the combined (CO) model revealed that synoptic predictors could provide no statistically significant improvement to the CP model except at 72 h, where U1CA-400 is negatively correlated with intensity change. Easterlies 400 km poleward and westerlies equatorward of a storm would thus favor intensification, but because the term appears only at 72 h its physical significance is doubtful. When the combined model is screened against SHIFOR instead of CP, the term U02/C-600 (related to the vertical shear, see Appendix B for a description) does add significant skill at 24-48 h (Table 3). A similar term, U02/C-400, also appears in the screening for CO from CP and, though not significant at any one time period, is forced into the final version of CP and tested on simulated operational conditions as described below.

Table 3. Results of screening for synoptic (SY), combined (CO), and an experimental combined screening against SHIFOR instead of CP. Reduction of variance and selection order indicated as in Table 1. Refer to Appendix B for nomenclature of synoptic terms.

Predictor	Forecast Interval						Kept ?
	12 h	24 h	36 h	48 h	60 h	72 h	
Predictor selections for synoptic (SY) model							
U02-600	4.8 (1)	7.6 (1)	8.1 (1)	6.6 (2)			Y
FVT0-10		3.9 (2)	5.7 (2)	8.2 (1)	8.5 (1)	11.3 (1)	Y
Predictor selections for combined (CO) model							
CP	25.8 (1)	34.9 (1)	36.0 (1)	36.8 (1)	38.6 (1)	37.2 (1)	Y
U02/C-4	1.6	2.5	2.2	1.2	1.2	1.5	F
U1CA-400						5.3 (2)	Y
Synoptic predictors selected when SHIFOR is used in place of CP							
SHIFOR	25.5 (1)	29.5 (1)	31.5 (1)	33.5 (1)	35.0 (1)	33.6 (1)	Y
U02/F-6		4.0 (2)	4.4 (2)				F
U1CA-400					5.1 (2)		Y

Y = Predictor included in final forecast equations for all intervals
C = Predictor conditionally accepted and only included if actually selected as significant for that interval (applies to land effects only)
F = Predictor forced into final equations though not significant at 95 percent at any interval

D. Estimated operational performance

Whenever statistical prediction models are derived on archived information, the operational results are worse because 1) the operational cases are not part of the sample to which the model was fitted, and 2) operational estimates of predictors are more likely to contain errors than are the final or "best track" estimates. The effect is even more pronounced when the model uses "perfect-prog" predictors which are assigned archived analysis values (which can be thought of as "perfect forecasts") during development and evaluated with error-prone forecast values in operational use.

A "jack-knife" method was used to test the operational degradation of the model. In this procedure, the model is fitted to all of the years of record but one, and then verified on the omitted "independent" year. The process is repeated until the model has been verified on each year. The verification is made to resemble operational conditions even more by using operational data from the omitted year in place of best track data. The results are shown in Table 4 for the SY and CO models, for which the full jack-knife test is made. Errors for CP are obtained by evaluating the dependent data model and coefficients with operational predictors and verifying the predictions.

Verification is presented for two classes of storms depending upon land influences. The LAND category includes those cases which 1) passed within 100 km of land, or 2) were

Table 4. Jack-knife verification for SHIFOR and the CHIPS models (CP, SY, and CO) for 1975-1985. Quantities shown are the RMS errors by model and forecast interval.

NO LAND

Interval	Cases	SH	CP	SY	CO
12 h	317	4.30	6.84	4.88	6.78
24 h	269	6.85	7.92	7.96	7.94
36 h	205	8.64	8.80	9.90	8.72
48 h	196	9.44	9.96	11.04	9.97
60 h	136	9.02	8.84	10.15	9.18
72 h	134	9.34	9.64	11.52	9.99

LAND

Interval	Cases	SH	CP	SY	CO
12 h	64	7.22	9.34	7.82	9.42
24 h	51	9.76	9.35	9.63	8.94
36 h	31	10.49	9.13	10.94	8.57
48 h	27	12.04	11.53	12.93	11.11
60 h	23	12.87	13.75	15.81	12.76
72 h	15	9.67	9.46	8.77	8.60

forecast by NHC to pass within 100 km of land during the forecast interval being verified. All others are in the NO LAND category. Unfortunately, official NHC forecast positions are not archived if the storm was onshore at verification time, so the LAND verification is biased towards cases where landfall was predicted but did not occur. A storm forecast to move inland but which remains offshore will be filled too much by CP, so one would expect a negative bias in the verification, as well as inflated RMS errors.

SHIFOR is superior at all but 60 h (where CP is slightly better) in the NO LAND category, with RMS errors averaging 0.83 ms-1 less than CO and 0.74 ms-1 less than CP. Including the U1CA-400 term (significant only at 72 h) and the U02/C-400 term actually degrade CP rather than improving upon it. For the LAND category, CP and CO both outperform SHIFOR at all but 12 and 60 h. Curiously, the two synoptic predictors do improve CO over CP for the LAND category, although the reason for this is not apparent. Examination of the biases (not shown) reveals that SHIFOR overforecasts the LAND cases as would be expected, even though no actual landfalling cases could be verified. CO underforecasts the first 24 h, probably also due to the presence of landfalling cases in the dependent data and the lack of them in the verification.

Figs. 6-8 show some examples of forecasts produced by CP for different forecast tracks, dates, and initial conditions.

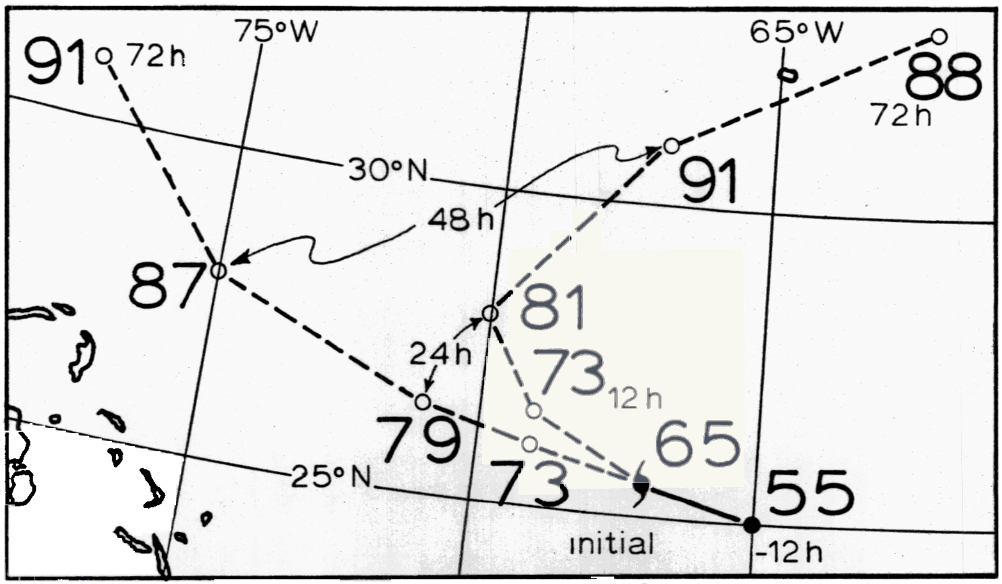


Fig. 6. Example of the effects forecast track on forecast intensity. numbers are intensities in knots.

Fig. 6 illustrates the effect of the forecast track on the forecast intensity. Both storms begin with initial intensity of 65 kt, increasing 10 kt in the past 12 h, but one is forecast to continue west-northwestward through 72 h, while the other is expected to recurve. Poleward acceleration (small V and large DYF) tends to favor intensification of the recurving storm over the first 48 h, but by 72 h the effect of cooler water has become dominant and it is weaker than the westward-moving counterpart.

Fig. 7 illustrates the effect of SST and time of year by comparing three storms with identical initial conditions and forecast track. In June, SST is a nearly constant 27.8^{0} C along the track and the storm attains an intensity of 79 kt at 36 h. In August, SST of 29.3^{0} C to 29.6^{0} C are among the warmest in the Atlantic basin, and the 36 h forecast is for 88 kt. October SSTs are slightly cooler than those of June south of 25^{0} N and over 2^{0} C cooler at the coast, but the forecasted intensities are almost the same, perhaps indicating that the synoptic conditions of late season are more favorable. More intense storms might also show a greater sensitivity to the SST capping effect.

Fig. 8 shows the effects of land and initial intensity. The track is that of the severe hurricane of September 1947. Initially the forecaster is faced with a 135 kt hurricane 12 h from the southeast Florida coast. Warnings would already be in effect. But with the 48 h position on the Gulf coast, the planners in New Orleans would already be concerned about the danger to their own community, including some idea of how strong the storm might be should it actually strike. The CP

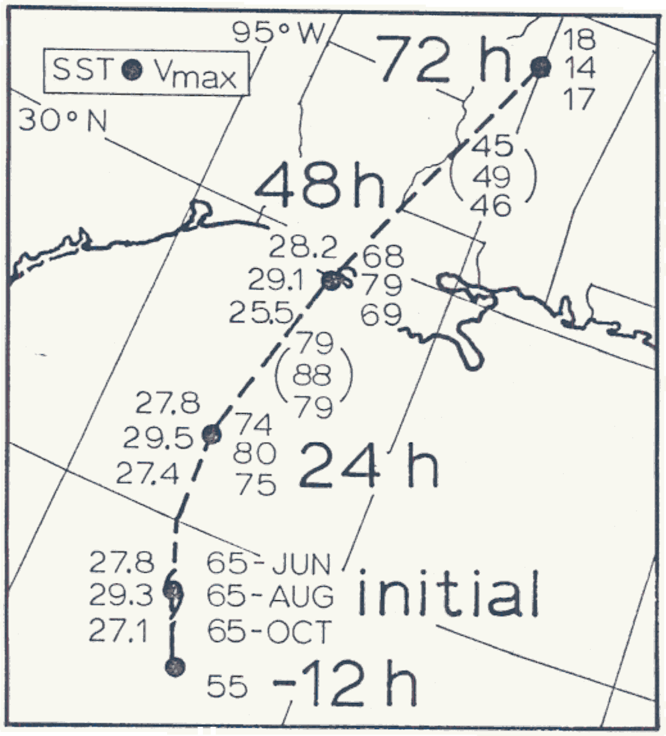


Fig. 7. Example of the effects of varying date and SST on forecast intensities of storms having identical forecast tracks. Numbers to left of track are SST's, numbers to right are forecast intensities in knots (June at top, October at bottom).

model indicates rapid filling from 135 kt to 84 kt as the hurricane crosses Florida, and a subsequent re-intensification to 101 kt in 36 h over the open Gulf of Mexico. Actual intensity at landfall was estimated at 80 kt. The CP forecast is rerun for an identical track but initial intensity 100 kt less. Land effects on so weak a system merely prevent it from deepening over land, and intensification commences immediately as the storm enters the Gulf of Mexico, with winds forecast to 49 kt by 36 h.

E. Suggested operational use of CHIPS

As indicated above, CP and CO represent an improvement over SHIFOR only because it can reproduce the influence of land in a manner consistent with the official track forecast. It is therefore suggested that both models be available to the forecaster, with CP emphasized only in landfalling cases where SHIFOR is invalid.

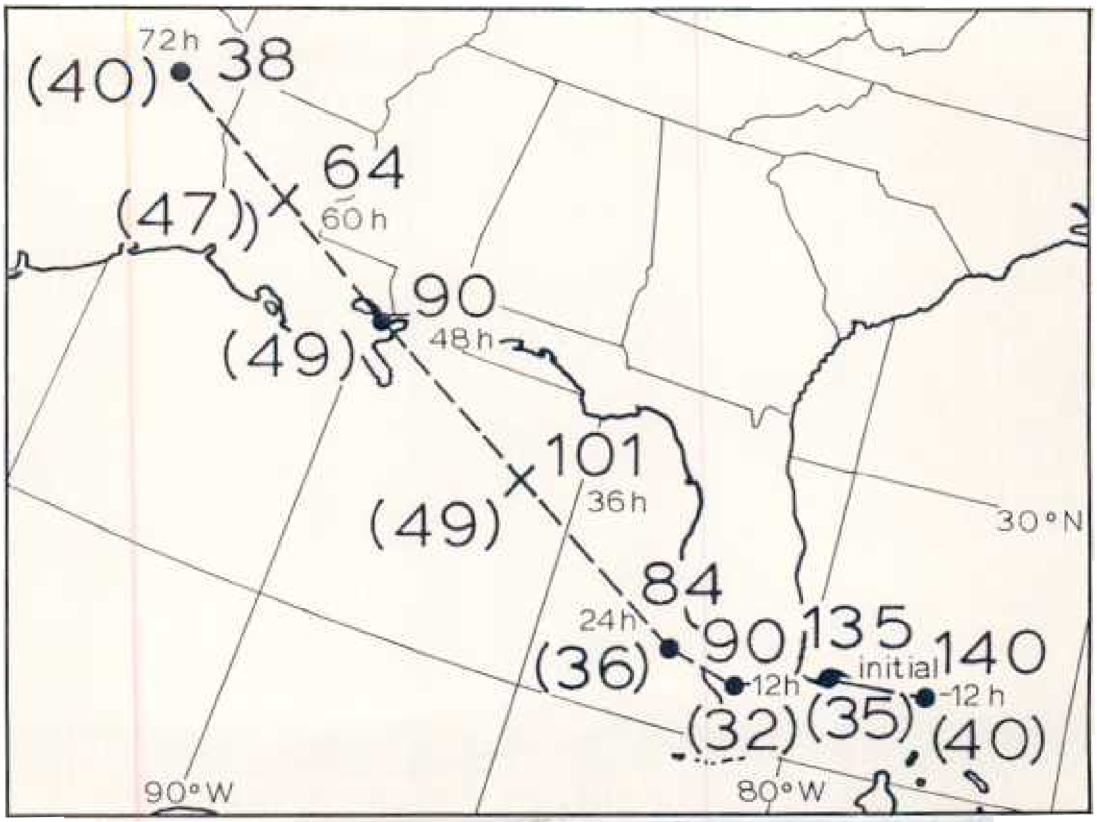


Fig. 8. Example of the effects of land on intensity forecasts for a severe hurricane and a minimal tropical storm. Large numbers above (hurricane) and below (tropical storm) the plotted track are intensities in knots.

V. DISCUSSION

The results of this study support the viewpoint of several authors including Merrill (1988) and Holland and Merrill (1984) that tropical cyclone intensity changes are influenced by environmental conditions, but also indicate that the relationships are weak ones and their usefulness as objective forecasting aids is limited. Several explanations are offered as a basis for discussion and future research in this area.

Poor results are often attributed to poor data quality. As a test, the quality of each dependent case was indexed by noting the octants of a 500 km-1000 km annulus centered on the storm in which an observation was present at 200 mb, and retaining only those cases in which no two adjacent octants lacked an observation. No significant increase in skill was noted for SY and CO models rescreened from this quality-controlled data set, indicating no sensitivity of the results to lack of data.

Another possibility is that the environmental influences hypothesized by Merrill (1988) are only qualitatively correct and must be generalized to include more details of the vortex structure itself in order to be quantitatively useful. It may well be that two vortices subject to identical environmental conditions might respond quite differently depending on their initial radius of maximum winds, vertical structure, and the like.

To be quantitatively successful, an environmental effects model may have to account for these differing responses related to the vortex structure. Previous discussions of the intensification process have tended to emphasize either vortex-scale processes or synoptic influences alone, but the prediction problem may require simultaneous treatment of some aspects of both scales.

VI. CONCLUSIONS

The following are the specific findings of the research described in this paper:

1) The hypothesis of Merrill (1988) that the climatological SST defines an upper bound on intensity holds for the period 1962-1985, and the capping function so defined contains more structure than would be expected from the empirical relationship of Miller (1958) or the theoretical development of Emanuel (1986).

2) The reduction of maximum winds of tropical cyclones proximate to major land masses are given by Eqs. 1-2. A tendency to weaken occurs when a tropical cyclone is within 100 km of a major land mass (approx. 2500 km^2 or more in area), with the magnitude of the effect proportional to the intensity. From 100-200 km from land, however, a tendency to intensify occurs. It is not known whether the latter has a physical basis.

3) Knowledge of the general structure of the wind field at 200 mb and in the low levels in the near environment (within 1000 km) of a tropical cyclone provides statistically significant information about future intensity changes, but provides no significant improvement beyond a prediction based on climatology and persistence alone. The weakness of the synoptic predictors cannot be attributed to insufficient data density.

4) The indicated relationships between 200 mb flow and intensity change are consistent with the environmental influence hypotheses of Merrill (1988) but explain less than 15% of

the variance. Other factors are either modulating the quantitative response to the environmental effects or else acting independently of them.

5) These results and those of Pike (1985) would seem to indicate that prediction of intensity change using classical statistical treatment of basic climatology and persistence and existing synoptic data or analyses has reached a dead end. Subsequent gains in our ability to predict intensity change depend upon the identification of the relative roles of environmental conditions and internal convective structures. Such understanding will require assemnbly and analysis of a data set containing observations of both scales, and/or numerical simulations involving variability on both scales.

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APPENDIX A

Statistical significance testing of predictors selected in stepwise regression

The statistical significance of a predictor selected in stepwise screening is determined by use of the F-test, but several modifications must be made because of the character of the data and the nature of the screening process.

First, the degrees of freedom associated with the sample size must be reduced because the individual cases in the dependent data sample are not actually independent observations. Successive observations from the same storm are correlated in time by an unknown amount. The "runs test" of Siegel (1956), as applied by Neumann (1979) was used here. The number of "runs" N_r (successive observations of the predictand above or below the predictand mean) is determined for the dependent data sample, and compared with the expected value, given by

$$E(N_r = [\ 2*N_a*N_b\ /\ (N_a+N_b)\ ] + 1, \qquad (A1)$$

where N_a and N_b are the observed number of observations above and below the mean, respectively. The ratio $E(N_r)/N_r$, where N_r is the observed number of runs, gives a "scaling factor" by which the sample size should be divided to estimate the degrees of freedom.

The CP model was screened from records at 6 h intervals, and the calculated scalings are 1.66, 2.03, 2.22, 2.27, 2.36, and 2.34 for forecast intervals of 12-72 h respectively. The SY and CO models use 12 h synoptic data so the temporal correlation from one case to the next is less, as expected, and the computed scalings are 1.21, 1.34, 1.54, 1.54, 1.69, and 1.73.

A second correction to the F-test is required because of the selection of a small number of predictors from a large number of potential predictors. Intuitively, out of 20 potential "predictors" which were actually random variables, one would be expected to test "significant" at the 95 percent level by chance alone. The additional play of chance introduced by selection from a pool of predictors is accounted for by testing at a much higher significance level which is equivalent to 95 percent for a single potential predictor. This "equivalent F test" is applied by computing the F statistic for the variable selected

$$F = (N_e - n_p - 1 \ * \ r^2 \ / \ 1 - r^2), \qquad (A2)$$

where N_e is the effective sample size (corrected for serial correlation), r is the partial correlation coefficient of the selected predictor, and n_p is the number of predictors already selected (including the one now being tested) and comparing it with the 95 percent "equivalent F" (Mills, 1958)

$$F^*_{.95} = F(\ 1 - 1/(20k)),$$

where $k = m - n_p + 1$ for m the number of potential predictors at the beginning of screening. Note that for the first selection from a pool of 100 potential predictors, the F statistic must exceed $F_{.9995}$ ($F^*_{.95}$ for k=100) for the predictor to be significant at 95 percent.

Since values of the F statistic are seldom tabulated for other than $F_{.95}$ and $F_{.99}$, the critical value of the equivalent F must be evaluated using an approximation such as that of Paulson (1942),

$$F_s = \left[\frac{ab + \sqrt{a^2b^2 - [a^2 - (1-a)x^2][b^2 - (1-b)x^2]}}{b^2 - (1-b)x^2} \right]^3$$

where x is the value of the standard normal variable for which the integrated probability from $-\infty$ to x is s, a = 7/9, and $b = 1 - 2/(9(N_e - n_p - 1)$.

The above corrections act to make the test for significance of added predictors more strict. One additional factor, that of non-independent predictors, would act to reduce the effective predictor pool size m_e to a value less than the actual m for the purposes of computing degrees of freedom and would therefore make $F^*_{.95}$ smaller and the test less rigid. The more rigid values are used in discussions of statistical significance throughout the text, and some predictors which are actually significant at 95 percent may therefore have been rejected.

APPENDIX B

Derivation and Nomenclature of Synoptic Predictors

The synoptic predictors are extracted from analyzed values of zonal (u) and tangential (v) wind at the ATOLL and 200 mb levels. Values are retrieved at cylindrical coordinate grid points using bilinear interpolation from the analysis grid, and transformed to coordinates moving with the storm by subtracting the past 12 h zonal or meridional storm motion, as appropriate.

The synoptic predictors themselves are the amplitudes of the wavenumber 0 and 1 discrete Fourier transforms of the wind components in azimuth, given by

$$\mathrm{X0L\text{-}R} = \sum_{i=1}^{8} x(i,R)/8$$

$$\mathrm{X1C\text{-}R} = \sum_{i=1}^{8} x(i,R) * \cos(\pi/4 * i$$

$$\mathrm{X1S\text{-}R} = \sum_{i=1}^{8} x(i,R) * \sin(\pi/4 * i), \text{ where}$$

i = octant (numbered clockwise from due north)
R = radius,
x(i,R) = wind component at octant i and radius R.

Predictors are identified by 1) wind component (U or V), 2) Fourier component (0, 1C, or 1S), 3) level (A for ATOLL and 2 for 200 mb), and 4) radius, in km. For example, U02-600 refers to the wavenumber-0 (azimuthal mean) zonal wind at 200 mb on a 600 km radius circle. Likewise, V1CA-800 is the wavenumber-1 cosine component of the ATOLL meridional wind at 800 km radius. Physically, this would represent a southerly flow north of the storm center, a northerly flow south of the storm center, and no meridional flow east or west of the center. Note that symmetric radial and tangential winds can be represented as sums of these wavenumber 1 components of zonal and meridional winds; the 600 km symmetric radial wind at 200 mb would be U1S2-600 + V1C2-600.

Other "supplementary" synoptic predictors computed from 200 mb winds are also made available to the screening algorithm. Relative zonal winds, representing vertical shear, are scaled by a non-dimensional Coriolis parameter C=2*sin(Y) (i.e. U02/C-600). Tangential winds (counterclockwise positive) are made available as well, with Coriolis scaling (CVT0-1000) and as squared terms (VT0**2-1000)