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PREDICTION OF AUGUST ATLANTIC BASIN HURRICANE ACTIVITY

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ABSTRACT

Although useful seasonal hurricane forecasts for the Atlantic basin are now a reality, large gaps remain in our understanding of observed variations in the distribution of activity within the hurricane season. The month of August roughly spans the first third of the climatologically most active part of the season though activity during this time can be highly variable. Otherwise active hurricane seasons can be very quiet during August while relatively inactive seasons can often be busy during this month. This paper reports on initial investigations of the prospects for forecasting this year-to-year variability of August tropical cyclone (TC) activity. The National Centers for Environmental Prediction/National Center for Atmospheric Research global reanalysis data set is used to identify and evaluate large-scale atmospheric precursor signals for predicting subsequent active versus inactive August periods. It is shown that 55-70 percent of the variance of August TC activity can be hindcast using combinations of three to five global predictive factors that are chosen from a 12 predictor pool with each of the predictors showing precursor associations with TC activity. The most prominent predictive signal is the equatorial July 200 mb wind off the west coast of South America. When this wind is anomalously strong from the northeast during July, Atlantic TC activity in August is almost always enhanced. Other July conditions associated with active Augusts include a weak subtropical high in the north Atlantic, an enhanced subtropical high in the northwest Pacific, and low pressure in the Bering Sea region.

One of the many applications of the August-only forecast includes incorporating it into the Gray et al. (1997) seasonal statistical forecast (issued on 1 August) to increase forecast skill for the full season prediction. Most importantly, predicted Net Tropical Cyclone (NTC) activity in August has a significant relationship with the incidence of U.S. August TC landfall events. Better understanding of August-only TC variability will allow for a more complete perspective of total seasonal variability and as such, assist in making better seasonal forecasts.

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LIST OF SYMBOLS AND ACRONYMS

ASO: August-September-October - The three-month period in the Atlantic basin that generally experiences the most tropical cyclone activity.

BI: Baroclinically-Initiated - A descriptive term that categorizes a tropical cyclone that forms from a non-tropical disturbance.

CDC: Climate Diagnostics Center, Boulder, Colorado

EN: El Niño - A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific.

ENSO: El Niño-Southern Oscillation

EOF: Empirical Orthogonal Function

GOM: Gulf of Mexico

H: Hurricane - A tropical cyclone with sustained low level winds of 74 miles per hour (33 ms^{-1} or 64 knots) or greater.

HD: Hurricane Day - A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or estimated to have hurricane intensity winds.

IH: Intense Hurricane - A hurricane which reaches a sustained 1 minute average 10 meter wind of at least 111 mph (96 kt or 50 ms^{-1}) at some point in its lifetime. This constitutes a category 3 or higher on the Saffir/Simpson scale (also termed a "major" hurricane).

IHD: Intense Hurricane Day - Four 6-hour periods during which a hurricane has intensity of Saffir/Simpson category 3 or higher.

MCS: Mesoscale Convective System

MJO: Madden/Julian Oscillation

NAO: North Atlantic Oscillation - A normalized measure of the surface pressure difference between Ireland and Portugal.

NCAR: National Center for Atmospheric Research, Boulder, Colorado

NCEP: National Centers for Environmental Prediction, Washington, DC

NH: Northern Hemisphere

NS: Named Storm - A hurricane or a tropical storm.

NSD: Named Storm Day - As in HD but for four 6-hour periods during which a tropical cyclone is observed (or is estimated) to have attained tropical storm intensity winds.

Niño 3.4 - Sea surface temperatures in the region from 5°N-5°S and 170-120°W.

Niño 4 - Sea surface temperatures in the region from 5°N-5°S and 160°E-150°W.

NTC: Net Tropical Cyclone activity - Average seasonal percentage mean of named storms, named storm days, hurricanes, hurricane days, intense hurricanes, and intense hurricane days. Gives overall indication of Atlantic basin seasonal hurricane activity.

PDO: Pacific Decadal Oscillation

SH: Southern Hemisphere

SIO: South Indian Ocean

SLPA: Sea Level Pressure Anomaly - The deviation of sea level pressure from observed long term average conditions.

SOI: Southern Oscillation Index - A normalized measure of the surface pressure difference between Tahiti and Darwin.

SST(s): Sea Surface Temperature(s)

SSTA(s): Sea Surface Temperature(s) Anomalies

TC: Tropical Cyclone - A large-scale circular flow occurring within the tropics and subtropics which has its strongest winds at low levels; including hurricanes, tropical storms, and other weaker rotating vortices.

TO: Tropical Only - A term used to describe a tropical cyclone that develops without mid-latitude influences.

TOH: Tropical Only Hurricanes

TONS: Tropical Only Named Storms

TS: Tropical Storm - A tropical cyclone with maximum sustained winds between 39 (18 ms^{-1} or 34 knots) and 73 (32 ms^{-1} or 63 knots) miles per hour.

ZWA: Zonal Wind Anomaly - A measure of upper level ($\sim$ 200 mb) west to east wind strength. Positive anomaly values mean winds are stronger from the west or weaker from the east than normal.

Chapter 1

INTRODUCTION

This study explores the potential for making extended-range forecasts of tropical cyclone (TC) activity for individual monthly portions of the Atlantic hurricane season. During the past twenty years large advances have occurred in our understanding of the seasonal variability of TCs. Seasonal hurricane forecasts for the Atlantic basin have shown significant skill (Fig. 1.1), especially forecasts issued each year on 1 August for named storm activity (Gray et al. 2001). There is, however, appreciable intraseasonal variability occurring on month-to-month and multi-week time scales within most seasons which has not been successfully forecast. Sometimes this variability is manifested as inactive periods of two-to-four weeks embedded within otherwise active seasons. Conversely, inactive seasons often exhibit short periods of intense activity. If these intraseasonal variations can be forecast, it will also provide useful insight on the nature of this variability. Additionally, accurate monthly forecasts will increase the utility of seasonal forecasts.

1.1 Previous Work

Prior to Gray (1984b), extended-range forecasting of TC activity was limited and tended to focus on issues related to potential predictability rather than actually attempting individual yearly forecasts. Ballenzweig (1959) was one of the first studies that distinguished active versus inactive TC months and studied differences in composites of the associated large-scale atmospheric fields. His report compiled and differenced active from inactive months during August to October and attempted to link the variable activity during these periods to circulation anomalies across the Northern Hemisphere (NH). He found that months of maximum TC activity were associated with a northeastward shift

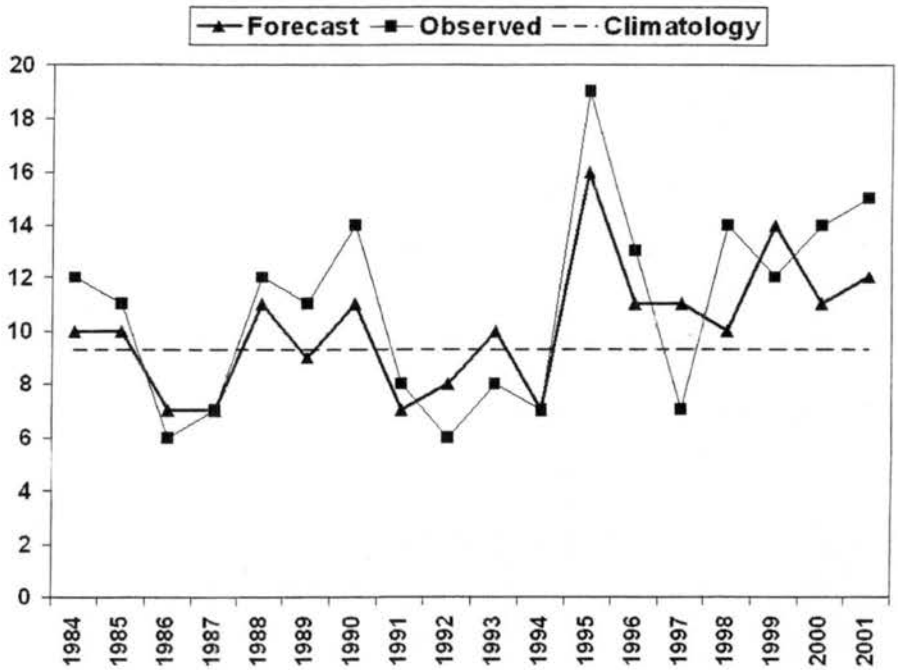

Figure 1.1: Comparative time series of 1 August forecast (solid line) versus observed total seasonal named storms (r = 0.80). The long-term climatological mean is shown by the dashed line.

of the low-level Atlantic sub-tropical anticyclone, thereby expanding and weakening the area of tropical easterlies equatorward of the ridge as shown in Fig. 1.2. Whereas Ballenzweig's study was diagnostic rather than prognostic, it introduced and illustrated the notion of observable mean differences between active and inactive periods occurring within the hurricane season on month-long time scales.

Dickson (1975) examined factors affecting August TCs in the eastern Pacific Ocean. He found that TC frequency increased when 700 mb height anomalies were positive over Baja California and the Gulf of Mexico to the north and east of the area of formation. This shift in the 700 mb height field was associated with a corresponding increase in trade winds during August in the western hemisphere from 20°N to 35°N. He also noted that eastern Pacific (10-20°N, 90-110°W) sea-surface temperatures (SSTs) had only a small positive correlation (r = 0.2) with TC activity. Though Dickson only used nine years of data in his study, he noted a displaced low-level ridge feature to the northeast of the prime area of TC formation, similar to what Ballenzweig (1959) had observed in the Atlantic.

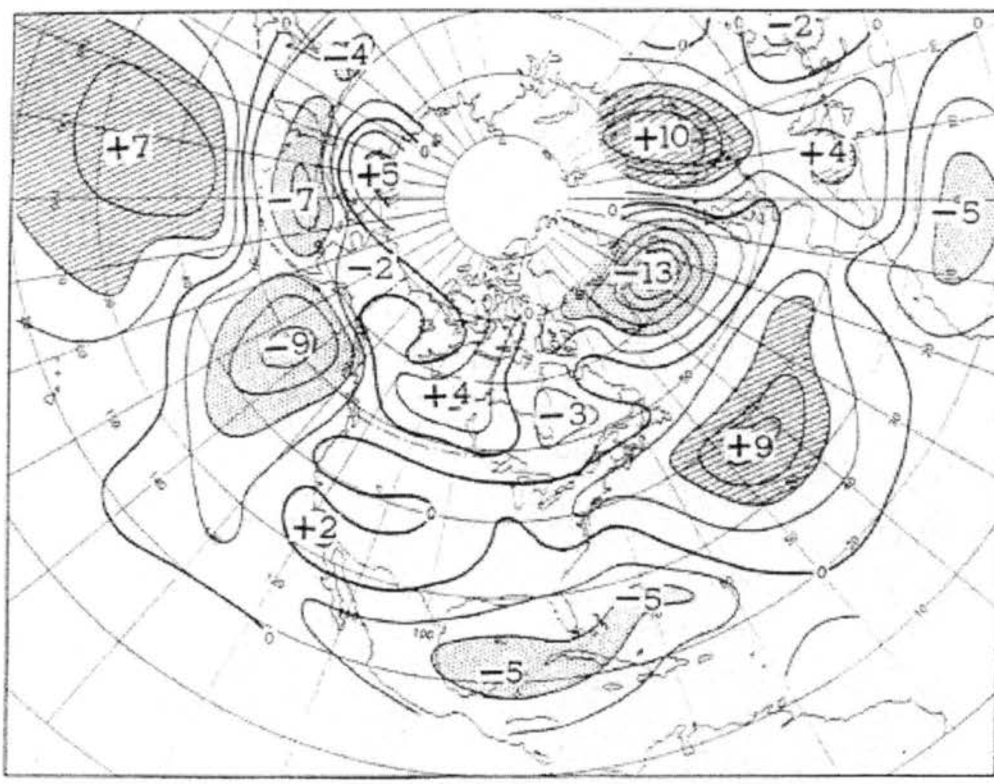

Figure 1.2: Analysis of composite anomalies associated with 700 mb height active (TC) August-October periods in the Atlantic basin (1933-1956). Figure reproduced from Ballenzweig (1959). A distinct shift of the Atlantic ridge to the north and east appears with low heights in the deep tropics. The enhanced subtropical ridge in the Pacific and lower heights in the Bering Sea are other significant features which are detailed in Chapter 5.

Both of these studies examined lag zero relationships and did not consider forecast factors. They demonstrated, however, that variations in the monthly to seasonal synoptic flow have significant effects on the frequency of TCs.

The next study to deal with short-term differences of TC activity was Shapiro (1987) who tested the predictability of monthly Atlantic TC frequency using monthly mean winds at 200 mb and 925 mb plus Sea Level Pressure Anomaly (SLPA) data poleward of 20°N. Winds over the Atlantic basin two months in advance of the August-September-October (ASO) active part of the hurricane season were composited and examined for predictive associations. Shapiro found statistically significant correlations between these winds and TC frequency encompassing approximately 45 percent of the hindcast variance. His findings suggested that the phase of the El Niño-Southern Oscillation (ENSO) was the strongest modulator of Atlantic TC activity on the monthly timescale though he estimated that only one-sixth of his skill was directly from ENSO. Shapiro deduced the ENSO relationship by noting that the leading empirical orthogonal function (EOF) of the Atlantic wind field was similar to the pattern found to the east of the ascending branch of a Walker cell. This branch is displaced eastward during El Niño creating easterly anomalies at the low levels and upper level westerly anomalies in the tropical Atlantic. The eleven years of data available to Shapiro were too limited to firmly establish stable correlations for individual months which eliminated the possibility of intraseasonal forecasts.

Recent findings by Maloney and Hartmann (2000) indicate that hurricane activity in the Gulf of Mexico (GOM) and western Caribbean Sea is significantly modulated by the passage of the Madden-Julian Oscillation (MJO) in some seasons. The MJO propagates eastward across the tropics as a wavenumber one oscillation with a period of about 30-45 days. The authors noted a fourfold increase of western Caribbean and GOM genesis events when MJO-linked wind anomalies (defined as the 850 mb u-component) were westerly across the eastern Pacific just south of Mexico. Maloney and Hartmann do not present any techniques to forecast TC activity but state that more accurate predictions of week-to-week genesis may be possible with further study and better forecasts of the MJO.

Demaria et al. (2001) were perhaps the first to utilize daily data for real-time forecasting of intraseasonal variations in Atlantic TC activity. These authors combined three sets of atmospheric variables associated with TC formation and intensification into an index which defines the favorability of current conditions for TC genesis compared with climatology. This "genesis parameter" is derived from the five-day running means of vertical wind shear, mid-level moisture, and vertical stability for the region of the tropical Atlantic east of the Lesser Antilles from 8-18°N and 55-35°W. This genesis parameter explains about 50 percent of the variance of intraseasonal TC activity that formed in this area during 1995-1999. The authors suggest that monitoring the genesis parameter on a daily basis provides an improved measure of the probability for a tropical wave to develop into a TC.

1.2 Objectives

The characteristics of monthly intraseasonal variability that the previous authors have studied can be illustrated with a few examples. During the very active 1961 season, net TC activity occurred at a level which was more than twice that of the annual mean climatology. However, no TCs were observed during August of 1961 which is an unusual occurrence, happening only twice since 1944. A contrasting situation was noted during 1976 wherein August activity was approximately twice the normal incidence yet the season ended with total seasonal activity which was only about 86 percent of average. Both the 1958 and 1966 hurricane seasons were 40 percent above average but August 1958 was almost three times as active as August 1966, hence an example of two active seasons which had vastly different levels of activity during August. Figures 1.3 and 1.4 show similar comparisons for six active and six inactive years, respectively. The widely-varying levels of August activity suggest that for a given season, the potential August TC activity can be very large.

Net Tropical Cyclone activity (NTC) for a given season is defined as the average of the aggregate seasonal percentage of six indices of Atlantic hurricane activity wherein a value of 100 represents an average season (Gray et al. 1994). Table 1.1 shows an example calculation. Further evidence of significant intraseasonal variability lies in the observation

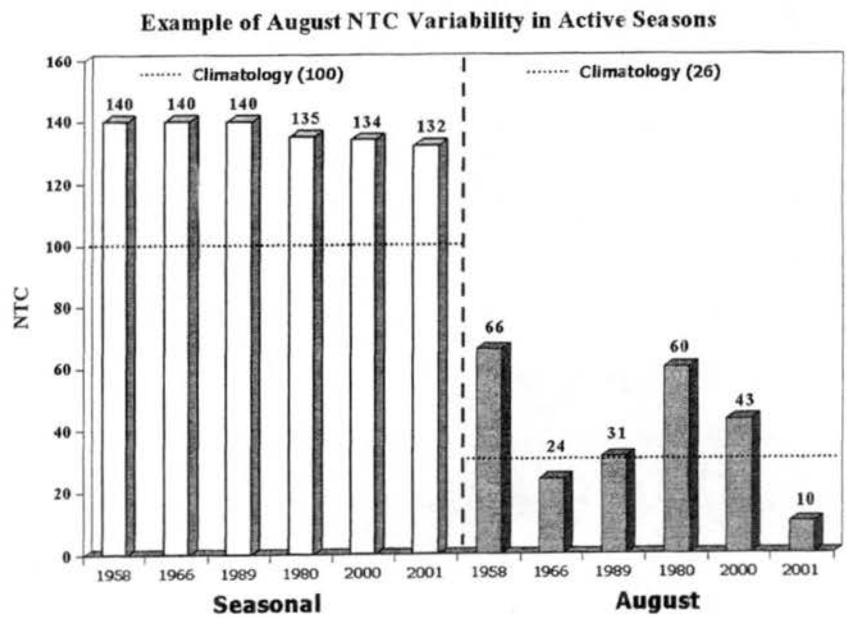

Figure 1.3: Additional examples of August NTC variability (shown shaded on the right) during active seasons which are shown on the left. Average (climatology) activity for both seasonal and August-only activity are indicated by the dotted lines.

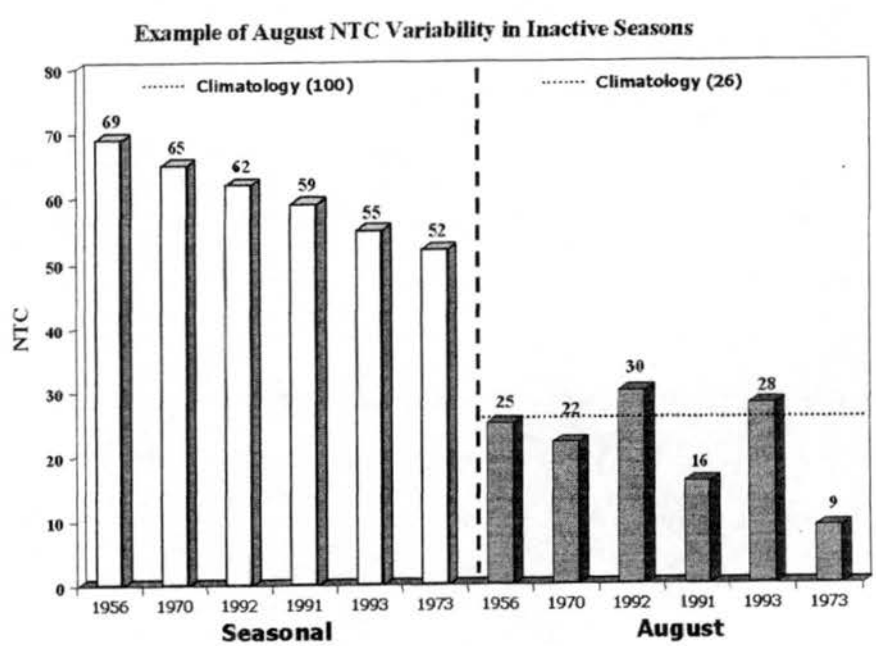

Figure 1.4: As in Fig. 1.3 but for August NTC variability during inactive seasons.

that NTC during August correlates with seasonal NTC at r = 0.65, explaining only about 39 percent of the total seasonal variance and vice versa. Similarly, Gray and colleagues' seasonal forecast scheme explains about 20 percent of the August NTC hindcast variance and it was apparent that new forecast techniques needed to be developed for shorter-period, sub-seasonal predictions.

Table 1.1: Illustration of how seasonal NTC is calculated as the mean of anomalies for the six seasonal parameters listed below. For example, a season with 10 NS, 50 NSD, 6 H, 25 HD, 3 IH, and 5 IHD would then be one-sixth of the sum of the following ratios: 10/9.4 = 106, 50/46.9 = 107, 6/5.8 = 103, 25/23.7 = 105, 3/2.2 = 136, 5/4.7 = 106, for a NTC of 111.

	1950-1990 Average	
1)	Named Storms (NS)	9.4
2)	Named Storm Days (NSD)	46.9
3)	Hurricanes (H)	5.8
4)	Hurricane Days (HD)	23.7
5)	Intense Hurricanes (IH)	2.2
6)	Intense Hurricane Days (IHD)	4.7

The methodology used in this paper differs from the current norm of initial value numerical modeling climate research in the science community. This study is directed to an analysis of how the atmosphere has worked in the past, utilizing the global dataset of the NCEP/NCAR reanalysis. One assumption used is that the atmosphere/ocean system will behave similarly in future years as it has in the past fifty years. Long-term climate signals are found (using the reanalysis dataset) and used to develop the August-only TC forecast. This study focuses on empirically-based techniques for making these predictions.

Though extended-range seasonal hurricane forecasts have now been issued for nineteen years, techniques for predicting subseasonal trends in Atlantic TC activity over periods of a few weeks to a month have not been available. This study utilizes NCEP/NCAR reanalysis data in developing hindcast schemes for nine measures of TC activity for August plus landfall probabilities based on forecast NTC. The forecast techniques that have been generated include both linear regression and analog models. The August-only forecast, when used as an additional potential predictor in the Gray et al. (1997) seasonal hurricane forecast scheme, significantly augments the seasonal forecast skill in hindcast tests. In addition to refining the seasonal forecast techniques, this study considers the relationships between predictors and the nature of their direct or indirect influence on August TC activity.

Chapter 2

TROPICAL CYCLONE DATA AND CLIMATOLOGY OF AUGUST ACTIVITY

2.1 Tropical Cyclone Data

August TC information was taken from the "best track" data base maintained by the National Hurricane Center (NHC) in Miami, Florida. The term "best" in this context alludes to the analysis method used in preparation of the data base. All available track and intensity estimates were used to prepare a smoothed post-analysis comprised of the most accurate storm information (Neumann et al. 1999). For this study, all TCs whose life cycle spanned any portion of August were tallied and stratified by their maximum intensity during August. The basic activity parameters calculated are the number of days that a TC maintained its intensity status during August as a named storm (NS), hurricane (H), and intense hurricane (IH). This method thus takes into account TCs that formed in July and persisted into August but considered only the portion of activity that occurred during August. July TCs lasting into August are somewhat rare though some have been quite notable (e.g., Allen 1980).

August TCs were also classified on the basis of their origins as suggested by Hess et al. (1995). One such origin-linked class considered here is termed "tropical-only" (TO) formations. The TO systems are defined as those hurricanes that formed without any obvious mid-latitude influences. These systems typically develop from African easterly waves equatorward of 23.5°N and move in a westward direction. An alternative origin-linked TC formation class was termed "baroclinically-initiated" (BI) hurricanes wherein non-tropical disturbances were involved. The latter class may include storms that develop along a stationary front, from a decaying mid-latitude low or from a Mesoscale Convective System

(MCS) emerging from North America (Elsner and Kara 1999). Baroclinically-initiated systems tend to form at somewhat higher latitudes in a more baroclinic environment close to areas of mid-latitude westerly flow and over ocean surface water that could be 1-2° cooler than the surface temperatures associated with TO cyclones.

Hess et al. (1995) showed that substantial gains in seasonal forecasting skill could be obtained by separately forecasting the incidence of TO versus BI systems. Since August is the first month wherein both TO and BI systems usually form, August TCs were classified using the same criteria as Hess et al. (1995) to determine if this approach could be utilized for improved August predictions. Classifying TCs at the time they first reached tropical storm intensity as either TO or BI categories posed an additional problem since Hess et al. (1995) only considered hurricanes. It was decided that the key criterion for categorizing a NS as a TONS was that it develop from a tropical wave without any contribution by mid-latitude influences. The latter was in accord with the National Hurricane Center "end of the season" summaries published in Monthly Weather Review and consultations with former project member Todd Kimberlain. Note however that a TONS that subsequently became a hurricane due to non-tropical enhancement effects remained a TONS but was not considered a TOH. Regression techniques for both TOH and TONS formations were developed in this study. Though BIH and BINS forecast equations were tested, no August-only BI forecasting technique proved successful.

2.2 Climatology

This section presents a summary of the main climatological qualities of August TC variability. August was chosen for this initial test of practical monthly TC forecasting for several reasons: August is the second busiest month in the Atlantic basin with a strong tendency for significant year-to-year variability. August is a transition time in the Atlantic hurricane season when systems typically begin to form from African easterly waves in the deep tropics. This change in formation type is significant as tropical cyclogenesis from African waves accounts for about 65 percent of all hurricanes (Pasch and Avila 1994) and 80 percent of the intense hurricanes that form in the basin (Landsea 1993). August is the first month wherein a comparatively high percentage of hurricanes form from these tropical waves, allowing greater predictability than exists earlier in the season when a much larger portion of storms that form do so with the aid of mid-latitude influences.

August is the second most active month, on average, encompassing about 26 percent of the total seasonal Atlantic NTC. The latter value has ranged from a high of 67.6 percent (1983) to a low of zero percent (1961, 1997) as shown in Table 2.1. Figure 2.1 shows that August activity lags far behind September which comprises about 47 percent of the season. Despite this large mean difference, August NTC was greater than September NTC values in 13 of the past 51 years. These 13 seasons tended to have below normal total seasonal NTC as can be seen by inspection of Table 2.2.

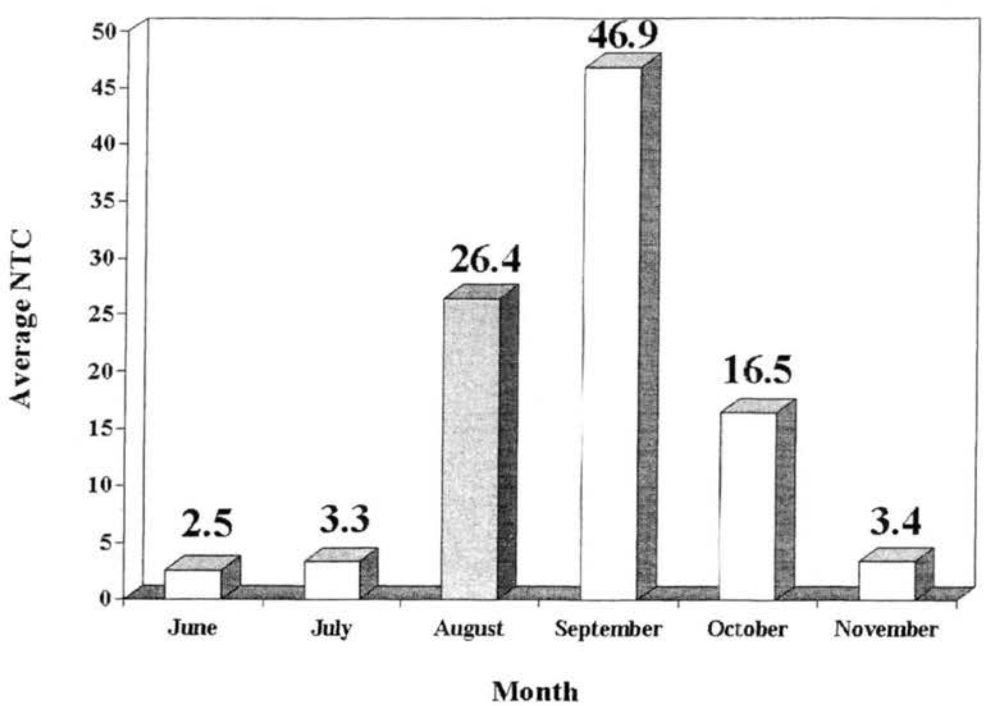

Figure 2.1: Summary of long-term mean NTC by month (1949-1999). An additional one percent of NTC occurs outside the official six month June 1-November hurricane season shown in the figure.

On average August has approximately three TCs, two of which become hurricanes (H) and one of which becomes an intense (Saffir-Simpson Scale Category 3 or higher) hurricane (IH). Table 2.3 presents a summary of statistics for average and extreme levels

Table 2.1: Comparison of year-by-year and long-term mean seasonal NTC versus August NTC. The column on the right shows the percent of seasonal NTC that is observed in August. The maximum value in each column is shown in bold print while minimums are in italic.

Year	Seasonal NTC	August NTC	Percent of Seasonal NTC
1949	115	32.3	28.1
1950	**243**	71.6	29.5
1951	121	31.7	26.2
1952	97	12.1	12.4
1953	121	13.5	11.2
1954	127	12.1	9.5
1955	198	**89.7**	45.3
1956	69	24.7	35.8
1957	86	2.4	2.8
1958	140	66.3	47.3
1959	99	2.3	2.3
1960	101	9.4	9.3
1961	222	*0.0*	*0.0*
1962	33	9.5	28.8
1963	116	30.8	26.6
1964	168	37.6	22.4
1965	86	14.9	17.3
1966	140	24.4	17.4
1967	97	2.3	2.4
1968	41	8.0	19.5
1969	157	60.7	38.6
1970	65	22.1	33.9
1971	95	18.0	18.9
1972	*28*	10.8	38.7
1973	52	9.3	18.0
1974	76	29.3	38.5
1975	92	22.4	24.4
1976	85	51.4	60.4
1977	46	6.1	13.4
1978	86	16.2	18.8
1979	96	36.3	37.8
1980	135	60.0	44.5
1981	114	10.6	9.3
1982	37	2.9	7.9
1983	32	21.6	**67.6**
1984	77	6.5	8.4
1985	110	21.8	19.8
1986	38	7.2	19.0
1987	48	15.6	32.4
1988	121	6.5	5.4
1989	140	31.1	22.2
1990	104	45.5	43.8
1991	59	16.1	27.3
1992	62	30.2	48.7
1993	55	27.6	50.2
1994	37	10.7	28.8
1995	237	76.4	32.3
1996	199	64.6	32.5
1997	54	*0.0*	*0.0*
1998	170	51.0	30.0
1999	193	61.0	31.6
Ave.	104.3	26.4	25.4

Table 2.2: List of years since 1949 wherein August NTC was greater than September NTC along with the corresponding total seasonal NTC values. As discussed in Section 1.2, mean NTC (longterm) is 100.

Year	August NTC	September NTC	Seasonal NTC
1956	24.7	15.7	69
1962	9.5	3.1	33
1968	8.0	5.7	41
1969	60.7	55.6	157
1970	22.1	21.1	65
1972	10.8	9.2	28
1976	51.4	23.0	85
1980	60.0	48.4	135
1983	21.6	9.8	32
1990	45.5	18.8	104
1992	30.2	27.6	62
1993	27.6	23.4	55
1994	10.7	4.7	37
Average	29.4	20.5	69.5

Table 2.3: Summary of mean and extreme values of observed August TC activity parameters for 1949-1999.

TC Activity Parameter	Mean	Standard Deviation	Maximum	Year	Minimum	Year
Named Storms (NS)	2.8	1.7	8	1995	0	1997*
Named Storm Days (NSD)	11.6	9.7	46.00	1995	0	1997*
Hurricanes (H)	1.6	1.2	5	1995	0	1997*
Hurricane Days (HD)	5.7	5.8	25.25	1995	0	1997*
Intense Hurricanes (IH)	0.6	0.7	2	1999*	0	1997*
Intense Hurricane Days (IHD)	1.3	2.1	8.5	1955	0	1997*
Net Tropical Cyclone Activity (NTC)	26.4	22.6	89.7	1955	0	1997*
Tropical Only Named Storms (TONS)	1.9	1.7	8	1995	0	1997*
Tropical Only Hurricanes (TOH)	1.0	1.2	5	1995	0	1997*

*Most recent occurrence

of August activity. Note that no TCs were observed during August in 1961 and 1997 and that zero is the minimum value for all statistics. The total number of named storms in August ranges as high as eight with as many as five hurricanes. Table 2.4 shows all August activity from 1949-1999 with the maximum value for each parameter shown in bold. Tropical-only (TO) hurricanes account for 62.5 percent of all hurricanes forming in August. This value is similar to the seasonal average wherein TOH comprise 63 percent of all seasonal hurricanes.

Within the historical record the August 1893 hurricane season is regarded as the most active. Data for 1893 year are cataloged at the bottom of Table 2.4. There were 5 TCs during that month, all of which became hurricanes, recording a tremendous 62 NSD (the climatological average NSD for an entire season is about 47) and 38 hurricane days. Two of the 1893 hurricanes were intense and spanned a total of eleven days. Even though some aspects of the intensity data are open to question (especially for IHD), the NTC for August 1893 is an incredibly large 126, considerably greater than anything observed during the past fifty Augusts. This is especially remarkable given that only twenty years since 1950 have had a <u>seasonal</u> NTC greater than the August 1893 level.

It is interesting to consider inter-relationships among the various TC parameters. Table 2.5 is a covariance matrix showing the linear correlation between all TC parameters. Though most of the indices in this table are closely associated, the NS and IH values are not well correlated. A large number of NS in August is only weakly indicative that an above average number of IH will form. An example is August 1995 wherein eight NS occurred, but only one of these reached IH status. Conversely, only four NS were observed in August 1999, two of which were IH. This dichotomy clearly suggests that conditions favorable for TC formation are not necessarily the same as conditions conducive to their strengthening into powerful storms. These differences result in different predictors being chosen for NS versus IH as detailed in Chapter 4.

August TC landfalls in the United States are a relatively common occurrence. Table 2.6 gives a brief summary of statistics on U.S. August landfall. Thirty-nine TCs have come

Table 2.4: Summary of August Atlantic tropical cyclone data for the years 1949-1999. The columns (from left to right) indicate the August total of NS (named storms), NSD (named storm days), H (hurricanes), HD (hurricane days), IH (intense hurricanes), IHD (intense hurricane days), NTC (Net Tropical Cyclone activity), TONS (tropical-only named storms) and TOH (tropical-only hurricanes). Bold type indicates the maximum value in each column for the period. Data for the most active August on record (1893) are summarized in the last row at the bottom of the table.

Year	NS	NSD	H	HD	IH	IHD	NTC	TONS	TOH
1949	3	12.50	2	6.75	1	1.25	32.3	3	2
1950	4	31.00	4	18.00	**2**	4.00	71.6	4	4
1951	3	13.00	1	7.25	1	1.75	31.7	3	1
1952	2	8.00	1	4.00	0	0.00	12.1	2	1
1953	3	8.50	1	3.25	0	0.00	13.5	1	0
1954	2	6.50	1	4.75	0	0.00	12.1	2	1
1955	5	36.75	3	19.75	**2**	**8.50**	**89.7**	5	3
1956	1	9.25	1	8.00	1	1.00	24.7	1	1
1957	1	1.75	0	0.00	0	0.00	2.4	0	0
1958	4	20.50	3	12.25	**2**	5.50	66.3	4	3
1959	1	1.50	0	0.00	0	0.00	2.3	1	0
1960	2	5.00	1	1.75	0	0.00	9.4	1	0
1961	0	0.00	0	0.00	0	0.00	0.0	0	0
1962	2	5.75	1	1.50	0	0.00	9.5	0	0
1963	2	12.50	2	9.75	1	0.75	30.8	2	2
1964	4	13.75	1	6.50	1	3.00	37.6	2	1
1965	2	7.25	2	4.25	0	0.00	14.9	1	0
1966	1	10.00	1	8.50	1	0.75	24.4	1	1
1967	1	1.50	0	0.00	0	0.00	2.3	1	0
1968	1	4.00	1	2.75	0	0.00	8.0	0	0
1969	6	21.25	3	12.75	**2**	2.75	60.7	4	2
1970	3	8.25	1	2.25	1	0.50	22.1	2	1
1971	4	8.00	2	3.25	0	0.00	18.0	2	0
1972	2	5.50	1	3.50	0	0.00	10.8	0	0
1973	2	6.75	1	0.75	0	0.00	9.3	2	1
1974	3	7.50	2	3.75	1	1.50	29.3	2	1
1975	2	5.25	2	2.75	1	0.50	22.4	1	1
1976	6	24.75	4	14.50	1	0.75	51.4	2	1
1977	1	1.75	1	1.25	0	0.00	6.1	0	0
1978	4	6.50	2	1.50	0	0.00	16.2	1	1
1979	3	8.50	1	4.75	1	4.00	36.3	3	1
1980	3	17.75	3	13.00	1	6.50	60.0	2	2
1981	2	10.75	1	0.50	0	0.00	10.6	1	0
1982	1	3.25	0	0.00	0	0.00	2.9	1	0
1983	2	6.50	2	2.25	1	0.25	21.6	1	1
1984	3	3.25	0	0.00	0	0.00	6.5	2	0
1985	3	11.75	3	5.25	0	0.00	21.8	2	2
1986	1	5.25	1	1.00	0	0.00	7.2	0	0
1987	3	17.25	1	1.75	0	0.00	15.6	1	0
1988	3	3.25	0	0.00	0	0.00	6.5	1	0
1989	4	21.00	3	11.25	0	0.00	31.1	4	2
1990	7	22.75	3	7.50	1	1.00	45.5	5	2
1991	1	4.00	1	2.25	1	0.25	16.1	0	0
1992	1	9.75	1	4.25	1	3.25	30.2	1	0
1993	4	17.00	1	4.50	1	0.25	27.6	3	0
1994	2	8.00	1	2.00	0	0.00	10.7	1	1
1995	**8**	**46.00**	**5**	**25.25**	1	1.75	76.4	**8**	**5**
1996	4	21.75	3	11.25	1	7.25	64.6	4	3
1997	0	0.00	0	0.00	0	0.00	0.0	0	0
1998	5	20.50	2	13.00	1	3.50	51.0	4	2
1999	4	26.75	3	14.25	**2**	3.00	61.0	4	3
Ave.	2.8	11.56	1.6	5.67	0.6	1.25	26.4	1.9	1.0
1893*	5	62.00	5	38.00	2	11.00	126.0	N/A	N/A

Table 2.5: Cross correlation matrix showing associations between nine August TC indices for the 51 years of 1949-1999.

	NS	NSD	H	HD	IH	IHD	NTC	TONS	TOH
NS	—	0.83	0.77	0.72	0.50	0.41	0.76	0.85	0.68
NSD	0.83	—	0.85	0.93	0.65	0.61	0.91	0.86	0.85
H	0.77	0.85	—	0.85	0.59	0.50	0.83	0.74	0.84
HD	0.72	0.93	0.85	—	0.71	0.67	0.93	0.82	0.88
IH	0.50	0.65	0.59	0.71	—	0.73	0.85	0.60	0.67
IHD	0.41	0.61	0.50	0.67	0.73	—	0.83	0.56	0.63
NTC	0.76	0.91	0.83	0.93	0.85	0.83	—	0.83	0.86
TONS	0.85	0.88	0.74	0.82	0.60	0.56	0.83	—	0.86
TOH	0.68	0.85	0.84	0.88	0.67	0.63	0.86	0.86	—
Average	0.69	0.81	0.75	0.81	0.66	0.62	0.85	0.77	0.78

ashore during the past 51 years, an average of about one TC every 1.3 years. Hurricane landfalls during August happen less frequently (approximately one in every two years) and ten intense hurricanes (one every five years) have made landfall in August during the period. Multiple August hurricane strikes are a relatively rare event, with only six instances during the past 100 years. The occurrence of two or more IH landfalls on the U.S. coast in August has not been observed during the total (1871-present) historical record. Additional considerations for forecasting landfall probabilities for TCs on the U.S. coast are detailed in Chapter 6.

Table 2.6: Summary statistics for August United States landfall events by intensity class (1949-1999).

	Named Storms	Hurricanes	Intense Hurricanes
Landfalling TCs	39	23	10
Maximum in August	4	2	1
Average per year	0.76	0.45	0.20

2.3 How August activity relates to total seasonal activity

Another exercise considered possible relationships between August activity parameters and the seasonal totals. Table 2.7 displays a correlation matrix for August-only TC activity parameters versus total seasonal TC activity. The most reliable (i.e., most strongly correlated) August indicators for total seasonal activity are HD and TOH. Many of these parameters are strongly influenced by individual, long-lived hurricanes that usually form from tropical waves south of 20°N. If one of these systems occurs during August, it suggests that the deep tropics are likely to continue to be active for the remainder of the season. Thus, the incidence of TOH during August is an important indicator for seasonal activity yet to come. August TOH correlate with seasonal NTC at r = 0.72, hence explaining about 52 percent of the seasonal variance. When two or more TOH have occurred during August, seasonal NTC averages more than 50 percent above normal. Tables 2.8 and 2.9 provide additional detail on the relationships between an above average number of August TOH and seasonal NTC. Table 2.10 shows an even stronger connection between the occurrence of three or more August TOH and seasonal NTC. Specifically, three or more TOH during August strongly indicates a hyperactive hurricane season with a NTC above 200.

Table 2.7: Linear correlation matrix for total seasonal activity indices versus August-only parameters for the period of 1949-1999.

	Total NS	Total NSD	Total H	Total HD	Total IH	Total IHD	Total NTC	Total Average
August NS	0.67	0.64	0.59	0.48	0.35	0.20	0.48	0.49
August NSD	0.59	0.73	0.67	0.64	0.53	0.40	0.63	0.60
August H	0.48	0.59	0.62	0.52	0.43	0.28	0.50	0.49
August HD	0.58	0.74	0.74	0.73	0.57	0.48	0.69	0.65
August IH	0.36	0.45	0.54	0.47	0.51	0.28	0.47	0.44
August IHD	0.35	0.51	0.54	0.55	0.55	0.50	0.57	0.51
August NTC	0.55	0.69	0.71	0.66	0.59	0.45	0.65	0.61
August TONS	0.70	0.76	0.72	0.65	0.51	0.40	0.65	0.63
August TOH	0.60	0.72	0.73	0.68	0.64	0.49	0.72	0.65
Average	0.54	0.65	0.65	0.60	0.52	0.39	0.59	

2.4 Multidecadal variations

Gray (1990) and Gray et al. (1997) proposed that the recent twenty-five year (1970-1994) downturn of TC activity, especially intense hurricanes, was primarily due to variations in the broad-scale Atlantic thermohaline circulation for which North Atlantic (50-60°N, 10-50°W) SSTs are used as a proxy. Multi-decadal variations of the thermohaline circulation and associated ocean SST patterns tend to occur on periods of 30 years or

Table 2.8: Summary of those years between 1949-1999 wherein exactly two tropical-only hurricanes (TOH) occurred during August and the corresponding values for two seasonal activity parameters.

Year	Seasonal Total of Hurricanes	Seasonal NTC
1949	7	119
1963	7	117
1969	12	157
1980	9	137
1985	7	111
1989	7	138
1990	8	102
1998	10	178
Average	8.4	132

Table 2.9: As in Table 2.8 but for years wherein two or more tropical-only hurricanes (TOH) occurred during August (1949-1999) and the associated seasonal TC activity indices.

Year	TOH in August	Seasonal Total of Hurricanes	Seasonal NTC
1949	2	7	119
1950	4	11	243
1955	3	9	198
1958	3	7	140
1963	2	7	117
1969	2	12	157
1980	2	9	137
1985	2	7	111
1989	2	7	138
1990	2	8	102
1995	5	11	237
1996	3	9	199
1998	2	10	178
1999	3	8	193
Average	2.6	8.7	162

Table 2.10: As in Table 2.8 but for years wherein three or more tropical-only hurricanes (TOH) were observed during August (1949-1999) and the associated seasonal TC activity.

Year	TOH in August	Seasonal Total of Hurricanes	Seasonal NTC
1950	4	11	243
1955	3	9	198
1958	3	7	140
1995	5	11	237
1996	3	9	199
1999	3	8	193
Average	3.5	9.2	202

more. Broadscale North Atlantic SSTs were in a relatively "cool" phase from the early 1970s to the early 1990s which closely coincides with the most recent multidecadal period of reduced TC activity observed. However, north Atlantic SSTs have warmed dramatically since mid-1995 with a return to a SST configuration more closely resembling that of the 1940s and 50s. Since this shift in the SST pattern in 1995, an unprecedented amount of TC activity has occurred. The past seven years has seen the development of 94 NS, 58 H and 27 IH with an average NTC that has been 215 percent higher than the average for the 1970-1994 period.

It is of interest to consider multi-decadal signals in the August monthly data by compositing aggregate activity during the 1950-1969 and 1995-1999 time period (both of these periods judged to be during an active Atlantic Ocean thermohaline conditions) versus the inactive 1970-1994 period. Table 2.11 shows the differences between the two twenty-five year periods expressed both as comparative averages and as ratios. The most pronounced changes are for the most intense type of activity including the average number of IHD which was 232 percent greater during the "active thermohaline" period. Whereas August TO activity was notably suppressed during the weak thermohaline years, the incidence of higher latitude baroclinically-initiated (BI) systems may have increased; thirteen August BI hurricanes formed during the inactive era while only one developed during the active era.

Table 2.11: Comparison of August activity during 25 "active thermohaline" years (1950-1969, 1995-1999) versus 25 "inactive thermohaline" years (1970-1994). Thermohaline conditions are inferred from North Atlantic SSTA. Note the abundance of IHD and lack of significant BI activity during the active years.

Average	NS	NSD	H	HD	IH	IHD	NTC	TONS	TOH	BINS	BIH
1950-69, 1995-99	2.72	13.31	1.6	7.55	0.72	1.74	31.08	2.2	1.32	0.20	0.04
1970-94	2.8	9.77	1.52	3.75	0.44	0.75	21.43	1.6	0.68	0.88	0.52

Ratio	NS	NSD	H	HD	IH	IHD	NTC	TONS	TOH	BINS	BIH
Active/Inactive	0.97	1.36	1.05	2.01	1.64	2.32	1.45	1.38	1.94	0.23	0.08

It is notable that average August NTC increased during the active period to values roughly 45 percent greater than the long-term mean. This was less than the 66 percent increase of total seasonal NTC that occurred during the active decades. This result suggests that August TCs are not as greatly affected by the processes causing the recent Atlantic multi-decadal variability. A larger multi-decadal difference in activity occurs during the months of September and October. The reasons for this primarily late season change in multi-decadal activity are not clear but could relate to mean vertical shear conditions of the zonal wind in the tropical Atlantic. To illustrate, August has the lowest climatological shear values of the hurricane season. If shear increased uniformly over the deep tropics during the inactive era, August would be less affected than September and October. Further work is needed to confirm this conjecture

The development of this August-only TC climatology allowed the formulation of indices describing measures of August TC activity. Some of these August indices proved useful as precursor signs for the remainder of the season's activity. The global data and methodology used to create forecast equations for nine measures of TC activity are described in the next chapter.

Chapter 3

GLOBAL DATA AND FORECAST METHODOLOGY

3.1 Global Data

A large portion of the analyses done for this study utilized the NCEP/NCAR global reanalysis (Kalnay et al. 1996) data for 1949-1999 which have become available during the past five years. The recently completed reanalysis project is comprised of numerous atmospheric and SST fields integrated onto a 2.5° x 2.5° global grid. The analysis technique gives a realistic, consistent interpretation of large-scale weather features back to 1948 using standardized assimilation and interpolation methods. An example of the data is provided in Fig. 3.1. This compilation uses a "frozen" global data assimilation system for numerous sources, some of which were not available for the prior "operational" analyses. This unique re-analysis data set allows for comparison of recent climate data versus data from earlier years in an environment free of artificial "climate shifts" due to inaccurate data or changes in observational platforms or analysis procedures (Kalnay et al. 1996). This standardized methodology allows for meaningful global-scale intercomparisons between different years and different periods. The approach to identifying predictive relationships taken in this study was not possible before these global analysis data sets became available.

The extensive online data analysis and plotting resources at the Climate Diagnostics Center (CDC) facilitated the identification and evaluation of correlations between a wide variety of atmospheric data fields and August TC activity parameters. All TC statistics were tested for antecedent correlation with reanalysis data fields for prior months on the CDC web page, http://www.cdc.noaa.gov/correlation (see Smith and Brown 1998). This online correlation activity provided one approach to identifying areas of covariation (with

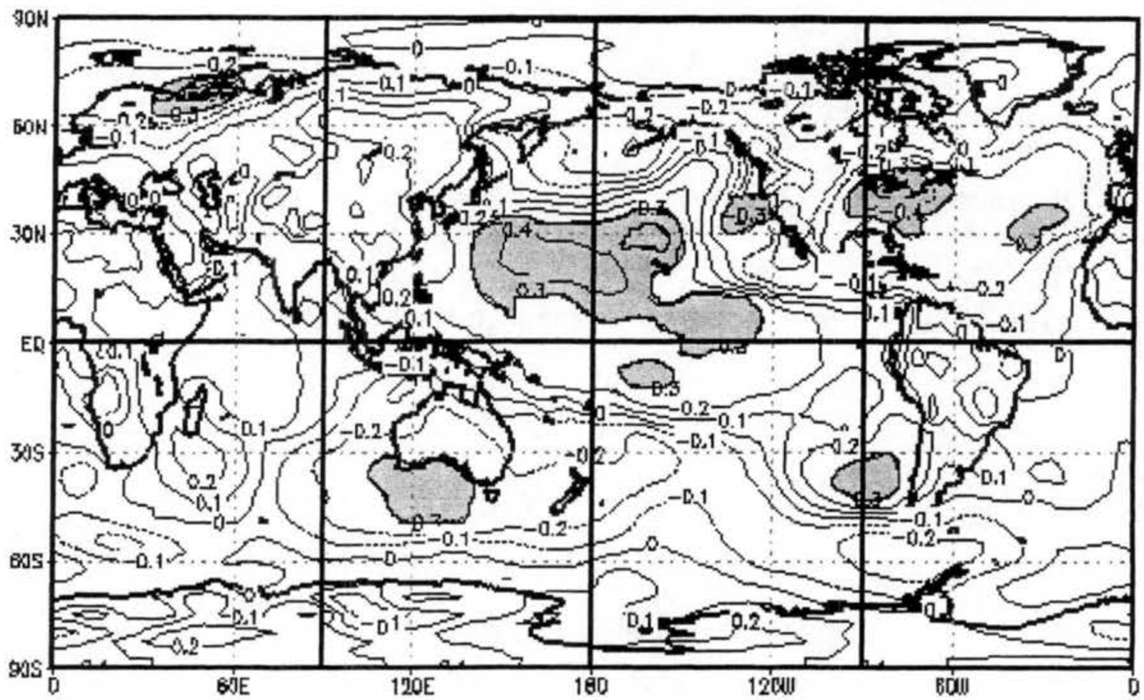

Figure 3.1: Analysis of correlation between July surface pressure and August NTC for the years 1958-1999. (Figure courtesy Climate Diagnostics Center.) Shading indicates correlations of greater than 0.3. Note areas of high correlations associated with the Atlantic and Pacific subtropical ridges.

TC activity indices) for possible use as predictors. The CDC reanalysis compositing site was similarly helpful for delineating broad areas with sharp circulation differences for active versus inactive Augusts at varying lag times in predictor data fields for any month of the year. A typical example given in Fig. 3.2 shows the difference field for July SLP associated with the highest 10 years minus the lowest 10 years of August NTC. The areas in the northern Pacific and northern Atlantic Oceans in Fig. 3.2 with strong SLP differences were used as predictors after undergoing additional testing as detailed in section 3.2.

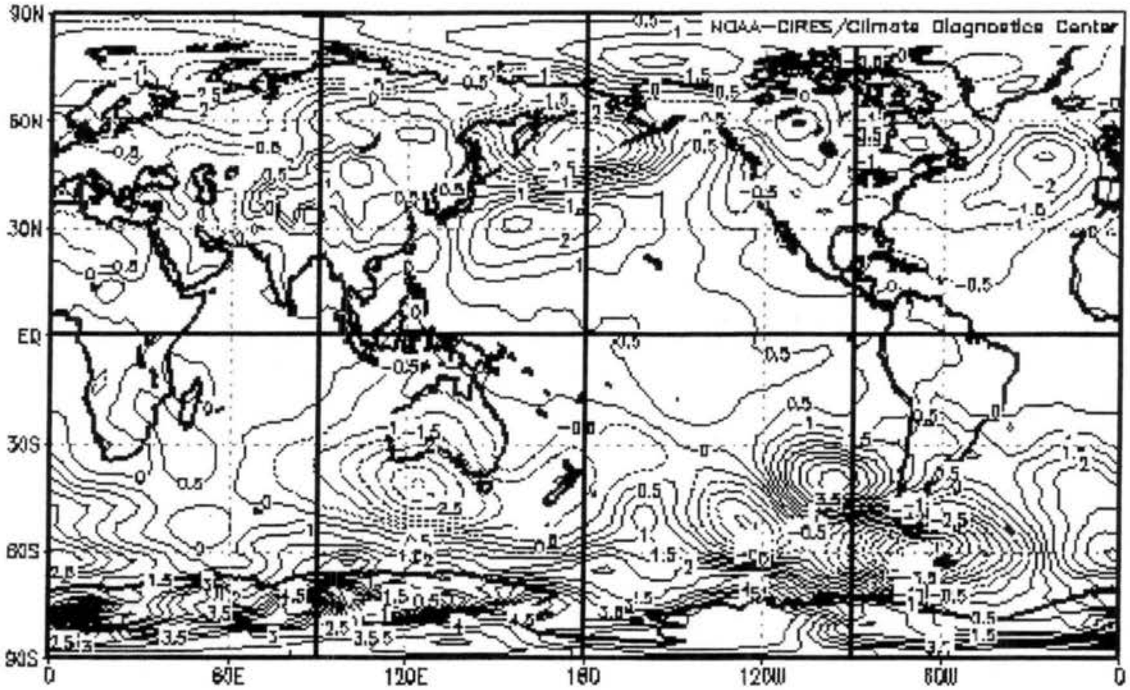

Figure 3.2: Composite difference for July SLPA (in mb) in the 10 most active Augusts (in terms of NTC) minus the 10 least active (NTC) Augusts. Negative numbers indicate areas where pressure was higher during the inactive years. The areas of strong differences in the Pacific southeast of Japan, in the Bering Sea and in the central Atlantic were used as predictors. (Figure courtesy of Climate Diagnostics Center.)

3.2 Methodology

The predictors identified by Gray et al. (1993) for an "August 1" seasonal forecast scheme (i.e., a forecast for seasonal activity which is promulgated on August 1) were utilized in a provisional first trial for forecasting August TC activity. This set of predictors failed to produce skillful forecasts and it was immediately clear that a new set of predictor factors would be required for skillful August-only forecasts. These new predictors were identified in several ways. First, the ten most active Augusts in the data record were composited and differenced versus the ten least active Augusts. As shown in the flow chart in Fig. 3.3, the method identified various global-scale difference fields which were then tested further as potential predictors. Another group of provisional predictors was identified by correlating TC activity indices with global reanalysis atmospheric fields for 1958-1999. Additional predictors were found later by correlating forecast residuals with global atmospheric signals.

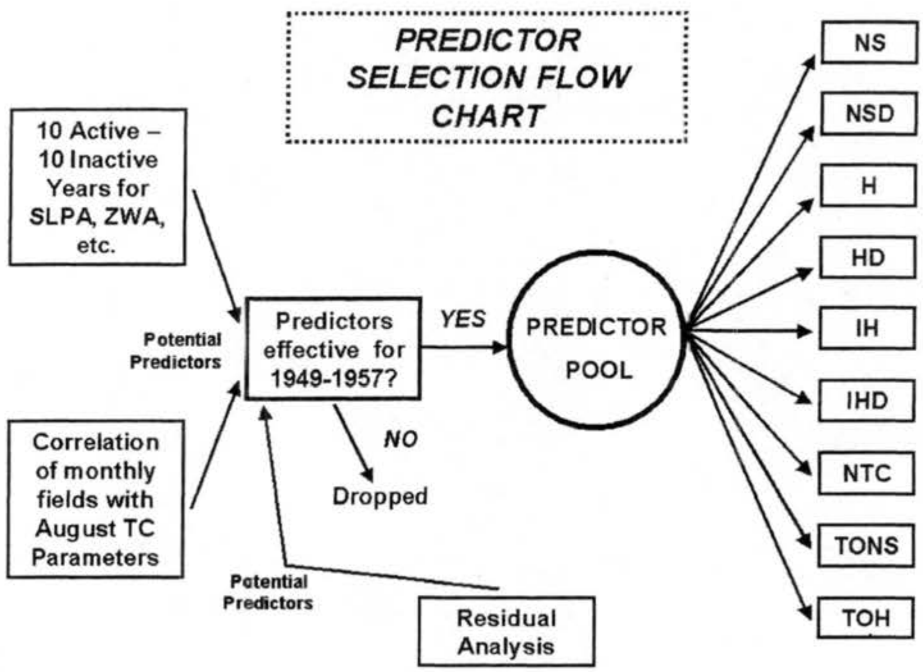

Figure 3.3: Flow chart detailing how provisional predictors for multivariate regression were chosen. (See text for explanation.)

Various predictors thus identified were extracted from the full reanalysis data set and condensed into time series of predictive indices. Provisional predictors were sought in four data fields: 200 mb u and v wind, 1000 mb geopotential height (correlates $> +0.98$ with surface pressure) and 500 mb height fields. These fields were selected based on the Gray et al. (1993) seasonal forecast scheme which uses 200 mb winds and surface pressures as predictors. These predictors were also used because they can be reliably estimated in real-time for application in a forecasting mode. The spatial domains of selected predictors were required to be of sufficient size so as to represent larger scale phenomenon where the smallest area used was 10° x 15°. This size constraint reduced the possibility of selecting areas with purely random correlations with the TC indices as predictors. The selection process was repeated numerous times to compile a pool of potential predictors which, after further qualifying tests, were tested in various combinations to maximize the amount of variance explained for each TC activity parameter.

A procedure used to further minimize the possibility of areas of chance favorable covariation being selected for predictor parameters was to limit the predictor selection data to the years 1958-1999 so that selected predictors could then tested against independent data during the first nine years (1949-1957) of the database. The early years were thus utilized as an independent data set to help determine if potential predictors were artifacts of chance correlation in the reanalysis data fields or were real representations of actual lagged physical teleconnection processes. Parameters that were not as effective for the early (independent data) period as in the later period were dismissed.

July SLPA provides a good example of the predictor selection process. The correlation map from the Climate Diagnostics Center (CDC) in Fig. 3.1 shows that an area of the North-Central U.S. correlates negatively (r = -0.40) with August NTC. However, the July pressures in that area during 1949-57 show very little relationship with August NTC (r = -.10), and this prospective predictor was dropped from the analysis.

A large pool of predictors was compiled to develop forecast equations from 51 years of data, providing regression coefficients and constants for each of the chosen predictors. The predictors were selected using an all-subset technique and included in the forecast equations until the inclusion of any additional predictor explained less than three percent of additional total variance, as recommended in Gray et al. (1994), or until five predictors were obtained. There is no explicit consideration of variance explained by individual predictors as occurs in stepwise regression. The "stepwise" technique attempts to identify the best combination of predictors for explaining the most total variance with the smallest number of predictors. The limitation of no more than five predictors also reduced the chance of overfitting. The correlation technique was an Ordinary Least sum of Square deviations (OLS) regression scheme. The weights of the coefficients and predictors were selected to fit each of the nine dependent variables (NS, NSD, H, HD, IH, IHD, NTC, TONS, TOH) in maximizing hindcast skill.

After the equations were developed the final step was performing a cross-validation (jackknife) procedure on the forecast models. This test, which was conducted following the guidelines suggested by Elsner and Schmertmann (1994), considers the extent to which each year can be predicted using data tat are independent of the predictor observations for that year. Thus, cross-validation in this paper consisted of predicting each year's TC activity for each of the 51 years in the sample using parameters derived from the other fifty years. The cross-validation hindcast results and observed values for all years were compared by computing their measure of agreement for each of the nine forecast parameters. This procedure partly emulates actual forecast conditions and provides some measure of the real predictive skill. It is notable that the cross-validation estimate of skill is generally regarded as an approximate upper boundary of real-time predictive ability.

The above methodology was utilized to develop skillful forecasts for August TC activity. The best predictors were found using an all-subset (rather than stepwise) regression technique. A limit of five predictors was set for each parameter and a total of twelve potential predictors were chosen for in creating the eight individual activity parameter forecast equations. The hindcast skill for each of these predictors is presented in the next chapter.

Chapter 4

HINDCAST TEST RESULTS

Hindcast schemes were developed for the 51-year period between 1949-1999 utilizing the best predictors for each of the nine dependent variables. Table 4.1 shows all hindcast values for the years 1949-1999 as well as the amount of variance (R^2) explained for each TC activity parameter. The predictions were surprisingly effective, typically explaining about 55-70 percent of the August TC variance. The map in Fig. 4.1 shows areas from which the predictor data were taken, Table 4.2 lists the predictors used with each equation and Table 4.3 provides additional specific information and details of the areas of the individual predictors along with the equations they were used in.

The most effective predictions were made for NTC where more than 80 percent of the NTC variance was accounted for by the hindcast equations. The statistical NTC (equation) hindcast explained about 73 percent of the NTC variance (Table 4.2). However, more skillful NTC hindcasts were obtained by calculating (forecast) NTC from the statistical forecasts for the six main NTC dependent variables (NS, NSD, H, HD, IH, IHD). This approach is termed as the "indirect" technique. In cases where the statistical forecast indicated negative values for any of the TC parameters, values of zero were substituted for that part of the indirect NTC calculation. Figure 4.2 shows the indirect NTC forecasts versus the observed values with the variance explained over 80 percent. A comparison between the statistical and indirect methods is shown in Table 4.4. The indirect method is considerably better than the direct statistical technique and is used as our primary August NTC forecast. Results obtained with the indirect technique are always shown for the hindcast values in all tables and figures.

Table 4.1: Experimental hindcast values for Atlantic August TC activity parameters. Variance explained for each parameter is shown in the last row at the bottom.

Year	NS	NSD	H	HD	IH	IHD	NTC	TONS	TOH
1949	3.53	12.94	1.39	6.63	1.09	1.65	33.66	1.86	0.77
1950	4.78	31.09	3.95	15.95	1.68	2.29	62.92	4.47	3.38
1951	3.42	12.31	1.45	5.87	0.75	2.15	32.02	2.04	0.91
1952	3.28	13.53	1.57	5.97	0.67	0.53	26.23	2.31	1.07
1953	2.83	5.66	0.92	2.75	0.69	0.58	18.89	1.79	0.50
1954	1.34	-0.10	0.22	-2.46	-0.11	-0.42	3.00	-0.20	-0.47
1955	4.86	28.65	3.51	16.47	1.44	4.72	68.11	4.17	3.05
1956	1.76	11.78	1.31	8.70	1.19	1.59	31.81	1.56	1.05
1957	1.93	0.47	-0.30	0.33	0.23	0.28	6.53	1.18	-0.73
1958	3.77	26.42	2.95	13.60	1.65	5.84	67.26	3.93	2.50
1959	1.19	4.62	0.79	1.34	0.26	0.75	11.55	1.60	0.53
1960	1.27	3.50	1.14	0.81	-0.22	0.06	7.55	0.92	0.42
1961	1.18	7.75	1.14	2.97	0.02	-0.61	10.37	1.57	0.66
1962	3.07	5.11	0.70	2.34	-0.08	0.71	13.45	0.93	0.14
1963	2.14	17.75	2.13	14.78	1.12	1.62	40.88	2.26	1.72
1964	2.56	13.95	2.11	5.52	1.06	3.74	40.72	1.76	1.47
1965	0.37	1.12	0.70	1.31	-0.02	0.23	4.78	0.48	0.11
1966	2.37	15.00	2.38	8.95	0.78	0.71	31.06	2.22	1.68
1967	1.23	2.88	0.67	-2.28	0.00	-1.26	5.09	1.39	0.16
1968	1.23	1.63	0.95	2.07	0.13	0.07	8.23	-0.58	-0.16
1969	3.10	12.78	1.48	8.12	1.03	0.74	30.47	2.22	1.16
1970	2.50	17.25	2.60	7.52	0.78	-0.18	29.25	2.14	1.74
1971	2.94	7.83	1.33	3.25	0.26	-0.38	16.09	0.89	0.61
1972	1.62	7.23	0.81	4.68	0.48	-0.54	14.73	0.77	0.23
1973	3.50	8.03	1.43	0.33	-0.04	-0.60	13.40	2.86	0.98
1974	1.89	8.50	1.31	4.61	0.94	1.07	24.26	1.85	0.73
1975	4.40	18.02	2.26	8.05	0.71	0.76	34.45	1.78	1.65
1976	3.34	18.55	2.42	10.00	0.80	1.77	38.86	1.07	1.50
1977	1.03	-2.77	0.18	-1.21	-0.18	0.84	5.32	-0.03	-0.60
1978	3.21	11.59	1.47	4.24	0.43	0.78	23.04	0.97	0.70
1979	3.43	12.71	1.79	7.26	0.66	4.24	40.85	2.80	1.41
1980	3.03	17.03	2.19	10.28	1.39	5.16	53.78	2.39	1.70
1981	2.97	10.40	1.30	2.87	0.06	0.63	17.39	1.82	0.84
1982	0.69	4.89	0.94	-1.07	0.10	-0.65	6.42	0.60	0.21
1983	2.69	13.07	1.89	4.27	0.39	0.60	22.99	1.88	1.28
1984	3.54	5.78	0.38	2.94	0.27	-0.06	13.55	1.36	0.12
1985	2.35	10.61	1.50	1.37	-0.06	-1.21	13.20	1.44	1.03
1986	1.21	10.10	1.51	5.48	0.26	-0.59	15.86	1.13	1.07
1987	3.64	12.80	1.48	4.81	0.58	0.27	23.97	1.57	0.77
1988	2.10	3.71	0.71	2.78	-0.02	0.62	11.27	1.72	0.30
1989	3.75	19.91	2.71	9.28	0.46	-0.02	31.50	4.43	2.37
1990	4.64	23.76	2.93	11.54	1.25	2.62	51.97	5.08	2.54
1991	2.41	9.29	1.09	4.66	0.73	2.29	27.59	1.03	0.55
1992	2.53	13.78	1.68	7.35	0.91	2.82	36.24	2.52	1.16
1993	3.26	11.77	1.40	4.79	0.56	1.19	25.85	1.83	0.93
1994	1.55	4.93	1.19	0.91	-0.34	-0.03	8.56	-0.06	0.35
1995	5.92	31.03	3.33	18.41	1.83	1.83	64.41	5.68	3.07
1996	3.37	10.53	2.00	8.26	0.92	6.38	50.88	2.04	1.45
1997	1.91	-2.67	0.23	-2.09	-0.20	0.01	4.07	0.21	-0.78
1998	4.83	21.79	2.61	12.27	1.19	4.60	57.75	4.48	2.41
1999	5.54	21.24	2.16	11.29	1.64	3.31	55.69	3.90	1.77
Variance Explained (R^2)	.55	.71	.57	.74	.72	.78	.86	.68	.64

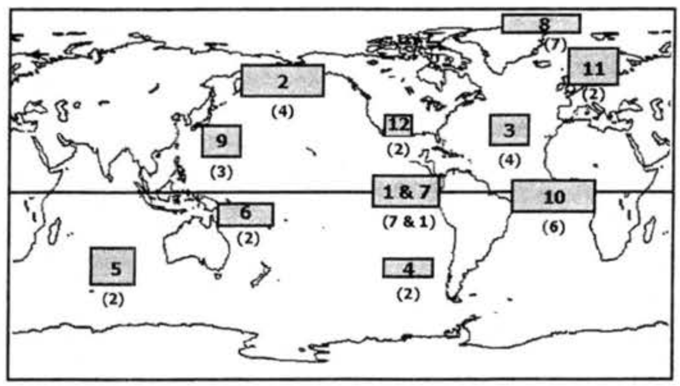

Figure 4.1: Global predictor map showing the locations of areas from which each predictor was derived. Table 4.2 provides a description of each predictor. The numbers under each box indicates how many times it was selected for a predictive equation and hence its importance in the hindcast equations.

Table 4.2: Listing of predictors chosen for forecasting each TC activity parameter and the total hindcast variance explained for each August activity parameter. A more detailed description of the 12 predictors is given in Table 4.3.

Forecast Parameter	No. of Predictors	Predictors Chosen from Table	Variability Explained by Hindcast (R^2) (1949-1999)	Likely Independent Forecast Skill (Jackknife)
NS	5	3, 6, 7, 9, 11	.55	.41
NSD	5	1, 2, 3, 8, 10	.71	.61
H	4	1, 2, 8, 10	.57	.47
HD	5	3, 4, 8, 9, 10	.69	.59
IH	5	1, 3, 5, 8, 12	.68	.59
IHD	5	1, 4, 5, 6, 9	.78	.72
NTC	5	1, 2, 8, 10, 12	.74	.66
TONS	4	1, 8, 10, 11	.68	.60
TOH	4	1, 2, 8, 10	.64	.56

1) Galapagos July 200 mb v - sign of correlation (-)
2) Bering Sea July SLP - sign of correlation (-)
3) Atlantic Ocean July SLP - sign of correlation (-)
4) SE Pacific July 200 mb u - sign of correlation (-)
5) S. Indian Ocean July 500 mb ht - sign of correlation (-)
6) Coral Sea July 200 mb u - sign of correlation (+)
7) Galapagos July 200 mb u - sign of correlation (-)
8) North Greenland June 200 mb u - sign of correlation (+)
9) Northwest Pacific June SLP - sign of correlation (+)
10) S. Atlantic Ocean April SLP - sign of correlation (-)
11) Scandinavia February SLP - sign of correlation (-)
12) SW USA January SLP - sign of correlation (-)

Considerable skill was also shown for other forecast parameters. Hindcasts for IHD were more accurate than for H or NS. Tables 4.5-4.13 show each individual forecast parameter and the exact order in which the predictors were chosen and Fig. 4.3 shows details of the predictor selection process for HD.

Table 4.3: Detailed listing of the area and utilization of all predictors for each individual hindcast parameter and the sign of each predictor correlation for an active TC August hindcast. See Fig. 4.1 for a map of these predictor locations.

Predictor and Sign of Correlation	Area	Eqs. Used In:
1) July 200 mb v wind (–)	4°S-8°N, 105-79°W	NSD, H, IH, IHD, NTC, TONS, TOH
2) July SLPA (–)	47-62°N, 156°E-164°W	NSD, H, NTC, TOH
3) July SLPA (–)	25-37.5°N, 47.5-25°W	NS, NSD, HD, IH
4) July 200 mb u wind (–)	40-35°S, 110-85°W	HD, IHD
5) July 500 mb height (–)	42.5-27.5°S, 72.5-95°E	IH, IHD
6) July 200 mb u wind (+)	17.5-7.5°S, 145-180°E	NS, IHD
7) July 200 mb u wind (–)	5°S-5°N, 110-85°W	NS
8) June 200 mb u wind (+)	80-85°N, 45°W-10°E	NSD, H, HD, IH, NTC, TONS, TOH
9) June SLPA (+)	18-30°N, 134-154°E	NS, HD, IHD
10) April SLPA (–)	10°S-5°N, 35°W-15°E	NSD, H, HD, NTC, TONS, TOH
11) February SLPA (–)	52.5-75°N, 5°W-35°E	NS, TONS
12) January SLPA (–)	30-40°N, 110-95°W	IH, NTC

Table 4.4: Summary of comparative statistics of two different hindcast tests (named versus indirect regression) for NTC.

Method	R^2	Jackknife R^2
Statistical Regression	.73	.66
Indirect Regression	.86	.75
Improvement	+.13	+.09

The most difficult parameter to forecast was NS. As shown in Table 4.5, only 55 percent of the August NS variability was explained and jackknife variance explained to only 41 percent. This result is likely due to a combination of effects including a basic problem wherein the difference between a 35 knot storm and a 30 knot depression is often rather subjective. Hence, changes in the warning policy at the National Hurricane Center as well as new observation techniques have almost certainly biased the NS data. Many more storms are being found in recent years as compared to before the availability of daily

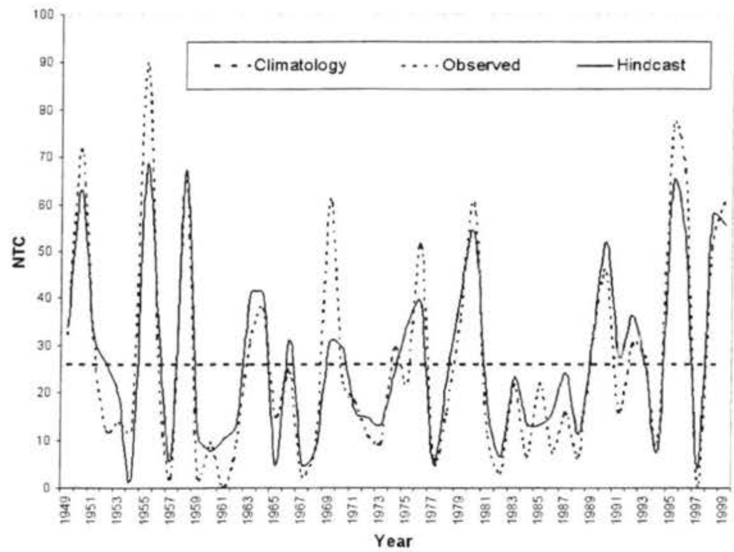

Figure 4.2: Smoothed time series showing August hindcast NTC (solid line) versus observed for 1949–1999. The variance explained (R^2) was 0.86.

Table 4.5: Listing of predictors chosen for predicting August NS and the amount of hindcast variance explained when all the years are compared with the jackknife (cross-validation) method (see Fig. 4.1 for the areas represented by the numbers)

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	7	.29	.22
Best Two Predictors	7, 11	.37	.28
Best Three Predictors	3, 6, 7	.46	.37
Best Four Predictors	3, 6, 7, 12	.51	.40
Best Five Predictors	3, 6, 7, 9, 11	.55	.41

Table 4.6: As in Table 4.5 but predictors chosen for NSD.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	7	.33	.25
Best Two Predictors	1, 10	.49	.41
Best Three Predictors	1, 2, 10	.64	.56
Best Four Predictors	1, 2, 8, 10	.68	.59
Best Five Predictors	1, 2, 3, 8, 10	.71	.61

Table 4.7: As in Table 4.5 but predictors chosen for H.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	2	.25	.19
Best Two Predictors	2, 7	.38	.30
Best Three Predictors	1, 2, 10	.53	.45
Best Four Predictors	1, 2, 8, 10	.57	.47

Table 4.8: As in Table 4.5 but predictors chosen for HD.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	8	.21	.14
Best Two Predictors	1, 10	.44	.35
Best Three Predictors	1, 2, 10	.57	.48
Best Four Predictors	1, 2, 8, 10	.63	.53
Best Five Predictors	3, 4, 8, 9, 10	.69	.59

Table 4.9: As in Table 4.5 but predictors chosen for IH.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	1	.24	.18
Best Two Predictors	1, 5	.40	.33
Best Three Predictors	1, 5, 8	.54	.46
Best Four Predictors	1, 3, 5, 8	.61	.53
Best Five Predictors	1, 3, 5, 8, 12	.68	.59

Table 4.10: As in Table 4.5 but predictors chosen for IHD.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	9	.26	.18
Best Two Predictors	4, 9	.51	.42
Best Three Predictors	4, 5, 9	.68	.61
Best Four Predictors	1, 4, 5, 9	.75	.68
Best Five Predictors	1, 4, 5, 6, 9	.78	.72

Table 4.11: As in Table 4.5 but predictors chosen for NTC.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	1	.30	.25
Best Two Predictors	1, 10	.49	.43
Best Three Predictors	1, 2, 10	.65	.59
Best Four Predictors	1, 2, 10, 12	.71	.64
Best Five Predictors	1, 2, 8, 10, 12	.74	.66

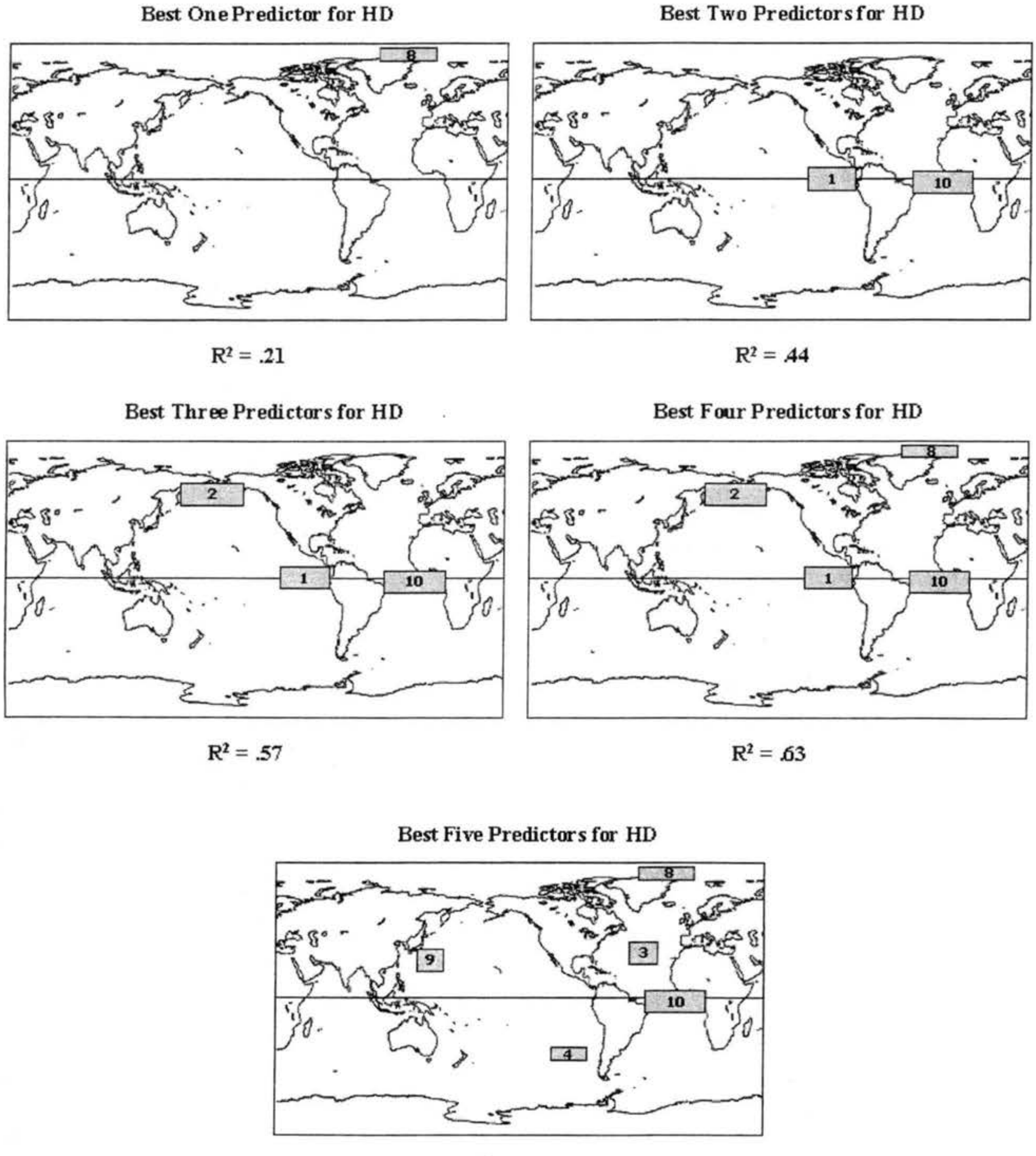

Figure 4.3: Location of predictors selected for the August HD forecast and the variance explained (R^2) for predictions based on one to five predictors.

Table 4.12: As in Table 4.5 but predictors chosen for TONS.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	7	.33	.26
Best Two Predictors	1, 10	.54	.48
Best Three Predictors	1, 10, 11	.65	.58
Best Four Predictors	1, 8, 10, 11	.68	.60

Table 4.13: As in Table 4.5 but predictors chosen for TOH.

Number of Predictors in Equation	Predictor(s) Chosen	R^2	Jackknife R^2
Best One Predictor	7	.25	.16
Best Two Predictors	1, 10	.47	.39
Best Three Predictors	1, 2, 10	.59	.52
Best Four Predictors	1, 2, 8, 10	.64	.56

satellite pictures (pre-1966). Another consideration is that a larger percentage of NS form from less-predictable non-tropical (BE and BI) sources is than either H or IH.

Even though the equations employ diverse selections of predictors, there are some notable similarities (see Table 4.2). First, all of the prediction August-only equations use some expression of the equatorial July 200 mb u or v wind parameter for the area just west of South America and nearly all of the equations utilize North Pacific Ocean ridge conditions by using data for either the Bering Sea or tropical West Pacific. Most of the hindcast equations also select a pressure term for early in the year, typically for either January or April. There are, however, substantial differences in the forecast equations for IH and IHD which distinguish them from the other predictive relationships. Notably, the equations for IH and IHD include parameters keyed to 500 mb height in the South Indian Ocean during July with no consideration of the April Atlantic Ocean pressure term.

Some statistical hindcasts (i.e., for August IH, HD) were combined by addition with other hindcasts to increase hindcast skill for one or the other of the parameters involved. For example, the final IH hindcast was obtained by combining the original IH hindcast with the HD hindcast, and similarly the HD hindcast was combined to the NSD hindcast for form the final HD hindcast. An example of the procedure is illustrated in Eq. 4.1 and

Table 4.14. These changes are possible due to the relatively high correlations between the parameters (see Table 2.5). Table 4.14 shows the hindcast skill values after being combined, which are typically five percent better than hindcasts made by simply using the statistical forecast alone for each parameter.

$$IH_{final} = 0.9(IH_{forecast}) + 0.1(HD_{forecast}) \tag{4.1}$$

Table 4.14: Improvement of hindcast skill after combination with other hindcast forecasts. See discussion relating to Eq. 4.1 for more details.

August-only Parameter	Before	After	Improvement
Hurricane Days (HD)	.69	.74	+.05
Intense Hurricanes (IH)	.68	.72	+.04

Another aspect of this study compared forecasts of August TO systems with forecasts for all (total) TCs. Table 4.15 shows hindcast variance explained for TO cyclones as compared to all TCs wherein in August TO cyclones are clearly more predictable. Hindcast variance explained was significantly greater for TO cyclones than was obtained for all cyclones using the same number of predictors. This result agrees well with Hess et al. (1995).

Table 4.15: Hindcast skill for tropical-only cyclones versus forecasts for all August cyclones using the same number of predictors (4).

Variance Explained: (R^2)	All Cyclones	Tropical Only Cyclones	Difference
Named Storms (NS)	.51	.68	+.17
Hurricanes (H)	.57	.64	+.07

Tables 4.16-4.24 present detailed year-by-year listings of the observed values versus hindcast values and residuals for each TC activity parameter. The final hindcast used for each parameter is shown in the tables. This includes the combination technique for HD and IH (see Eq. 4.1 and Table 4.14) and "indirect" technique for NTC (Table 4.4). The absolute means for each column are shown at the bottom of each table. Mean errors of

less than 1.0 for the NS, H, and IH forecasts suggests that a typical forecast of NS, H and IH would have an error of about one cyclone with a "bad" forecast being off by two or more cyclones.

The results in this chapter show strong hindcast skill for making monthly forecasts of August-only TC activity. In fact, August-only hindcast skill is significantly greater than has been developed for the seasonal forecast. The parameters developed for the August forecast are also quite different from those used for the seasonal TC predictions. These August-only predictors and their relationships to TC activity are discussed at length in Chapter 5.

Table 4.16: Year-by-year comparison of observed versus predicted results for Named Storms (NS). The residual (right column) is defined as the predicted minus observed value. Mean absolute value of the ratio residual/observed = 0.33.

Year	Observed	Predicted	Residual
1949	3	3.53	0.53
1950	4	4.78	0.78
1951	3	3.42	0.42
1952	2	3.28	1.28
1953	3	2.83	−0.17
1954	2	1.34	−0.66
1955	5	4.86	−0.14
1956	1	1.76	0.76
1957	1	1.93	0.93
1958	4	3.77	−0.23
1959	1	1.19	0.19
1960	2	1.27	−0.73
1961	0	1.18	1.18
1962	2	3.07	1.07
1963	2	2.14	0.14
1964	4	2.56	−1.44
1965	2	0.37	−1.63
1966	1	2.37	1.37
1967	1	1.23	0.23
1968	1	1.23	0.23
1969	6	3.10	−2.90
1970	3	2.50	−0.50
1971	4	2.94	−1.06
1972	2	1.62	−0.38
1973	2	3.50	1.50
1974	3	1.89	−1.11
1975	2	4.40	2.40
1976	6	3.34	−2.66
1977	1	1.03	0.03
1978	4	3.21	−0.79
1979	3	3.43	0.43
1980	3	3.03	0.03
1981	2	2.97	0.97
1982	1	0.69	−0.31
1983	2	2.69	0.69
1984	3	3.54	0.54
1985	3	2.35	−0.65
1986	1	1.21	0.21
1987	3	3.64	0.64
1988	3	2.10	−0.90
1989	4	3.75	−0.25
1990	7	4.64	−2.36
1991	1	2.41	1.41
1992	1	2.53	1.53
1993	4	3.26	−0.74
1994	2	1.55	−0.45
1995	8	5.92	−2.08
1996	4	3.37	−0.63
1997	0	1.91	1.91
1998	5	4.83	−0.17
1999	4	5.54	1.54
Ave.	2.76	2.76	|0.90|

Table 4.17: As in Table 4.16 but for observed and predicted results for Named Storm Days (NSD). Mean absolute value of residual/observed = 0.34.

Year	Observed	Predicted	Residual
1949	12.50	12.94	0.44
1950	31.00	31.09	0.09
1951	13.00	12.31	-0.69
1952	8.00	13.53	5.53
1953	8.50	5.66	-2.84
1954	6.50	-0.10	-6.60
1955	36.75	28.65	-8.10
1956	9.25	11.78	2.53
1957	1.75	0.47	-1.28
1958	20.50	26.42	5.92
1959	1.50	4.62	3.12
1960	5.00	3.50	-1.50
1961	0.00	7.75	7.75
1962	5.75	5.11	-0.64
1963	12.50	17.75	5.25
1964	13.75	13.95	0.20
1965	7.25	1.12	-6.13
1966	10.00	15.00	5.00
1967	1.50	2.88	1.38
1968	4.00	1.63	-2.37
1969	21.25	12.78	-8.47
1970	8.25	17.25	9.00
1971	8.00	7.83	-0.17
1972	5.50	7.23	1.73
1973	6.75	8.03	1.28
1974	7.50	8.50	1.00
1975	5.25	18.02	12.77
1976	24.75	18.55	-6.20
1977	1.75	-2.77	-4.52
1978	6.50	11.59	5.09
1979	8.50	12.71	4.21
1980	17.75	17.03	-0.72
1981	10.75	10.40	-0.35
1982	3.25	4.89	1.64
1983	6.50	13.07	6.57
1984	3.25	5.78	2.53
1985	11.75	10.61	-1.14
1986	5.25	10.10	4.85
1987	17.25	12.80	-4.45
1988	3.25	3.71	0.46
1989	21.00	19.91	-1.09
1990	22.75	23.76	1.01
1991	4.00	9.29	5.29
1992	9.75	13.78	4.03
1993	17.00	11.77	-5.23
1994	8.00	4.93	-3.07
1995	46.00	31.03	-14.97
1996	21.75	10.53	-11.22
1997	0.00	-2.67	-2.67
1998	20.50	21.79	1.29
1999	26.75	21.24	-5.51
Ave.	11.56	11.56	|3.92|

Table 4.18: As in Table 4.16 but for observed and predicted results for Hurricanes (H). Mean absolute value of residual/observed = 0.39.

Year	Observed	Predicted	Residual
1949	2	1.39	−0.61
1950	4	3.95	−0.05
1951	1	1.45	0.45
1952	1	1.57	0.57
1953	1	0.92	−0.08
1954	1	0.22	−0.78
1955	3	3.51	0.51
1956	1	1.31	0.31
1957	0	-0.30	-0.30
1958	3	2.95	−0.05
1959	0	0.79	0.79
1960	1	1.14	0.14
1961	0	1.14	1.14
1962	1	0.70	−0.30
1963	2	2.13	0.13
1964	1	2.11	1.11
1965	2	0.70	−1.30
1966	1	2.38	1.38
1967	0	0.67	0.67
1968	1	0.95	−0.05
1969	3	1.48	−1.52
1970	1	2.60	1.60
1971	2	1.33	−0.67
1972	1	0.81	−0.19
1973	1	1.43	0.43
1974	2	1.31	−0.69
1975	2	2.26	0.26
1976	4	2.42	−1.58
1977	1	0.18	−0.82
1978	2	1.47	−0.53
1979	1	1.79	0.79
1980	3	2.19	−0.81
1981	1	1.30	0.30
1982	0	0.94	0.94
1983	2	1.89	−0.11
1984	0	0.38	0.38
1985	3	1.50	−1.50
1986	1	1.51	0.51
1987	1	1.48	0.48
1988	0	0.71	0.71
1989	3	2.71	−0.29
1990	3	2.93	−0.07
1991	1	1.09	0.09
1992	1	1.68	0.68
1993	1	1.40	0.40
1994	1	1.19	0.19
1995	5	3.33	−1.67
1996	3	2.00	−1.00
1997	0	0.23	0.23
1998	2	2.61	0.61
1999	3	2.16	−0.84
Ave.	1.57	1.57	|0.62|

Table 4.19: As in Table 4.16 but for observed and predicted results for Hurricane Days (HD). Mean absolute value of residual/observed = 0.43.

Year	Observed	Predicted	Residual
1949	6.75	6.63	–0.12
1950	18.00	15.95	–2.05
1951	7.25	5.87	–1.38
1952	4.00	5.97	1.97
1953	3.25	2.75	–0.50
1954	4.75	-2.46	–7.21
1955	19.75	16.47	–3.28
1956	8.00	8.70	0.70
1957	0.00	0.33	0.33
1958	12.25	13.60	1.35
1959	0.00	1.34	1.34
1960	1.75	0.81	–0.94
1961	0.00	2.97	2.97
1962	1.50	2.34	0.84
1963	9.75	14.78	5.03
1964	6.50	5.52	–0.98
1965	4.25	1.31	–2.94
1966	8.50	8.95	0.45
1967	0.00	-2.28	–2.28
1968	2.75	2.07	–0.68
1969	12.75	8.12	–4.63
1970	2.25	7.52	5.27
1971	3.25	3.25	0.00
1972	3.50	4.68	1.18
1973	0.75	0.33	–0.42
1974	3.75	4.61	0.86
1975	2.75	8.05	5.30
1976	14.50	10.00	–4.50
1977	1.25	-1.21	–2.46
1978	1.50	4.24	2.74
1979	4.75	7.26	2.51
1980	13.00	10.28	–2.72
1981	0.50	2.87	2.37
1982	0.00	-1.07	–1.07
1983	2.25	4.27	2.02
1984	0.00	2.94	2.94
1985	5.25	1.37	–3.88
1986	1.00	5.48	4.48
1987	1.75	4.81	3.06
1988	0.00	2.78	2.78
1989	11.25	9.28	–1.97
1990	7.50	11.54	4.04
1991	2.25	4.66	2.41
1992	4.25	7.35	3.10
1993	4.50	4.79	0.29
1994	2.00	0.91	–1.09
1995	25.25	18.41	–6.84
1996	11.25	8.26	–2.99
1997	0.00	-2.09	–2.09
1998	13.00	12.27	–0.73
1999	14.25	11.29	–2.96
Ave.	5.67	5.67	|2.42|

Table 4.20: As in Table 4.16 but for observed and predicted results for Intense Hurricanes (IH). Mean absolute value of residual/observed = 0.46.

Year	Observed	Predicted	Residual
1949	1	1.09	0.09
1950	2	1.68	−0.32
1951	1	0.75	−0.25
1952	0	0.67	0.67
1953	0	0.69	0.69
1954	0	-0.11	−0.11
1955	2	1.44	−0.56
1956	1	1.19	0.19
1957	0	0.23	0.23
1958	2	1.65	−0.35
1959	0	0.26	0.26
1960	0	-0.22	−0.22
1961	0	0.02	0.02
1962	0	-0.08	−0.08
1963	1	1.12	0.12
1964	1	1.06	0.06
1965	0	-0.02	−0.02
1966	1	0.78	−0.22
1967	0	0.00	0.00
1968	0	0.13	0.13
1969	2	1.03	−0.97
1970	1	0.78	−0.22
1971	0	0.26	0.26
1972	0	0.48	0.48
1973	0	-0.04	−0.04
1974	1	0.94	−0.06
1975	1	0.71	−0.29
1976	1	0.80	−0.20
1977	0	-0.18	−0.18
1978	0	0.43	0.43
1979	1	0.66	−0.34
1980	1	1.39	0.39
1981	0	0.06	0.06
1982	0	0.10	0.10
1983	1	0.39	−0.61
1984	0	0.27	0.27
1985	0	-0.06	−0.06
1986	0	0.26	0.26
1987	0	0.58	0.58
1988	0	-0.02	−0.02
1989	0	0.46	0.46
1990	1	1.25	0.25
1991	1	0.73	−0.27
1992	1	0.91	−0.09
1993	1	0.56	−0.44
1994	0	-0.34	−0.34
1995	1	1.83	0.83
1996	1	0.92	−0.08
1997	0	-0.20	−0.20
1998	1	1.19	0.19
1999	2	1.64	−0.36
Ave.	0.59	0.59	|0.27|

Table 4.21: As in Table 4.16 but for observed and predicted results for Intense Hurricane Days (IHD). Mean absolute value of residual/observed = 0.56.

Year	Observed	Predicted	Residual
1949	1.25	1.65	0.40
1950	4.00	2.29	-1.71
1951	1.75	2.15	0.40
1952	0.00	0.53	0.53
1953	0.00	0.58	0.58
1954	0.00	-0.42	-0.42
1955	8.50	4.72	-3.78
1956	1.00	1.59	0.59
1957	0.00	0.28	0.28
1958	5.50	5.84	0.34
1959	0.00	0.75	0.75
1960	0.00	0.06	0.06
1961	0.00	-0.61	-0.61
1962	0.00	0.71	0.71
1963	0.75	1.62	0.87
1964	3.00	3.74	0.74
1965	0.00	0.23	0.23
1966	0.75	0.71	-0.04
1967	0.00	-1.26	-1.26
1968	0.00	0.07	0.07
1969	2.75	0.74	-2.01
1970	0.50	-0.18	-0.68
1971	0.00	-0.38	-0.38
1972	0.00	-0.54	-0.54
1973	0.00	-0.60	-0.60
1974	1.50	1.07	-0.43
1975	0.50	0.76	0.26
1976	0.75	1.77	1.02
1977	0.00	0.84	0.84
1978	0.00	0.78	0.78
1979	4.00	4.24	0.24
1980	6.50	5.16	-1.34
1981	0.00	0.63	0.63
1982	0.00	-0.65	-0.65
1983	0.25	0.60	0.35
1984	0.00	-0.06	-0.06
1985	0.00	-1.21	-1.21
1986	0.00	-0.59	-0.59
1987	0.00	0.27	0.27
1988	0.00	0.62	0.62
1989	0.00	-0.02	-0.02
1990	1.00	2.62	1.62
1991	0.25	2.29	2.04
1992	3.25	2.82	-0.43
1993	0.25	1.19	0.94
1994	0.00	-0.03	-0.03
1995	1.75	1.83	0.08
1996	7.25	6.38	-0.87
1997	0.00	0.01	0.01
1998	3.50	4.60	1.10
1999	3.00	3.31	0.31
Ave.	1.25	1.24	|0.69|

Table 4.22: As in Table 4.16 but for observed and predicted results for Net Tropical Cyclone activity (NTC). Mean absolute value of residual/observed = 0.26.

Year	Observed	Predicted	Residual
1949	32.3	33.7	1.40
1950	71.6	62.9	-8.70
1951	31.7	32.0	0.30
1952	12.1	26.2	14.20
1953	13.5	18.9	5.40
1954	12.1	3.0	-9.10
1955	89.7	68.1	-21.60
1956	24.7	31.8	7.10
1957	2.4	6.5	4.10
1958	66.3	67.3	1.00
1959	2.3	11.6	9.20
1960	9.4	7.6	-1.90
1961	0.0	10.4	10.40
1962	9.5	13.4	3.90
1963	30.8	40.9	10.10
1964	37.6	40.7	3.10
1965	14.9	4.8	-10.10
1966	24.4	31.1	6.70
1967	2.3	5.1	2.80
1968	8.0	8.2	0.20
1969	60.7	30.5	-30.20
1970	22.1	29.3	7.20
1971	18.0	16.1	-1.90
1972	10.8	14.7	3.90
1973	9.3	13.4	4.00
1974	29.3	24.3	-5.00
1975	22.4	34.5	12.00
1976	51.4	38.9	-12.50
1977	6.1	5.3	-0.80
1978	16.2	23.0	6.80
1979	36.3	40.9	4.50
1980	60.0	53.8	-6.20
1981	10.6	17.4	6.80
1982	2.9	6.4	3.50
1983	21.6	23.0	1.30
1984	6.5	13.5	7.10
1985	21.8	13.2	-8.60
1986	7.2	15.9	8.60
1987	15.6	24.0	8.40
1988	6.5	11.3	4.80
1989	31.1	31.5	0.40
1990	45.5	52.0	6.50
1991	16.1	27.6	11.50
1992	30.2	36.2	6.00
1993	27.6	25.9	-1.80
1994	10.7	8.6	-2.10
1995	76.4	64.4	-12.00
1996	64.6	50.9	-13.80
1997	0.0	4.1	4.10
1998	51.0	57.8	6.70
1999	61.0	55.7	-5.30
Ave.	26.38	26.38	|6.78|

Table 4.23: As in Table 4.16 but for observed and predicted results for Tropical-only Named Storms (TONS). Mean absolute value of residual/observed = 0.39.

Year	Observed	Predicted	Residual
1949	3	1.86	−1.14
1950	4	4.47	0.47
1951	3	2.04	−0.96
1952	2	2.31	0.31
1953	1	1.79	0.79
1954	2	−0.20	−2.20
1955	5	4.17	−0.83
1956	1	1.56	0.56
1957	0	1.18	1.18
1958	4	3.93	−0.07
1959	1	1.60	0.60
1960	1	0.92	−0.08
1961	0	1.57	1.57
1962	0	0.93	0.93
1963	2	2.26	0.26
1964	2	1.76	−0.24
1965	1	0.48	−0.52
1966	1	2.22	1.22
1967	1	1.39	0.39
1968	0	−0.58	−0.58
1969	4	2.22	−1.78
1970	2	2.14	0.14
1971	2	0.89	−1.11
1972	0	0.77	0.77
1973	2	2.86	0.86
1974	2	1.85	−0.15
1975	1	1.78	0.78
1976	2	1.07	−0.93
1977	0	−0.03	−0.03
1978	1	0.97	−0.03
1979	3	2.80	−0.20
1980	2	2.39	0.39
1981	1	1.82	0.82
1982	1	0.60	−0.40
1983	1	1.88	0.88
1984	2	1.36	−0.64
1985	2	1.44	−0.56
1986	0	1.13	1.13
1987	1	1.57	0.57
1988	1	1.72	0.72
1989	4	4.43	0.43
1990	5	5.08	0.08
1991	0	1.03	1.03
1992	1	2.52	1.52
1993	3	1.83	−1.17
1994	1	−0.06	−1.06
1995	8	5.68	−2.32
1996	4	2.04	−1.96
1997	0	0.21	0.21
1998	4	4.48	0.48
1999	4	3.90	−0.10
Mean	1.92	1.92	|0.75|

Table 4.24: As in Table 4.16 but for observed and predicted results for Tropical-only Hurricanes (TOH). Mean absolute value of residual/observed = 0.56.

Year	Observed	Predicted	Residual
1949	2	0.77	−1.23
1950	4	3.38	−0.62
1951	1	0.91	−0.09
1952	1	1.07	0.07
1953	0	0.50	0.50
1954	1	-0.47	−1.47
1955	3	3.05	0.05
1956	1	1.05	0.05
1957	0	-0.73	−0.73
1958	3	2.50	−0.50
1959	0	0.53	0.53
1960	0	0.42	0.42
1961	0	0.66	0.66
1962	0	0.14	0.14
1963	2	1.72	−0.28
1964	1	1.47	0.47
1965	0	0.11	0.11
1966	1	1.68	0.68
1967	0	0.16	0.16
1968	0	-0.16	−0.16
1969	2	1.16	−0.84
1970	1	1.74	0.74
1971	0	0.61	0.61
1972	0	0.23	0.23
1973	1	0.98	−0.02
1974	1	0.73	−0.27
1975	1	1.65	0.65
1976	1	1.50	0.50
1977	0	-0.60	−0.60
1978	1	0.70	−0.30
1979	1	1.41	0.41
1980	2	1.70	−0.30
1981	0	0.84	0.84
1982	0	0.21	0.21
1983	1	1.28	0.28
1984	0	0.12	0.12
1985	2	1.03	−0.97
1986	0	1.07	1.07
1987	0	0.77	0.77
1988	0	0.30	0.30
1989	2	2.37	0.37
1990	2	2.54	0.54
1991	0	0.55	0.55
1992	0	1.16	1.16
1993	0	0.93	0.93
1994	1	0.35	−0.65
1995	5	3.07	−1.93
1996	3	1.45	−1.55
1997	0	-0.78	−0.78
1998	2	2.41	0.41
1999	3	1.77	−1.23
Mean	1.02	1.02	|0.57|

Chapter 5

AUGUST PREDICTOR-ACTIVITY RELATIONSHIPS

As discussed in Chapter 3, the predictors for the Gray et al. (1993) August 1 seasonal (activity) forecast scheme were utilized in a first test for forecasting August TC activity. This approach showed little hindcast skill, and it was clear that a new set of August-specific predictors would be needed for an August-only model. A group of provisional predictors was identified by correlating TC activity indicators with global reanalysis atmospheric fields for 1958-1999. Predictors so identified in the 1958-1999 data but which were ineffective for the test years of 1949-1957 were discarded. Hindcast tests were then made for the years 1949-1999 after determining the best predictors for each of the eight dependent TC forecast variables. Twelve monthly predictors were determined to be related to some aspect to August TC activity. The combination of three to five of these predictors typically explained about 55-70 percent of the August variance of various TC activity parameters. Figure 5.1 again shows the areas of the globe from which they were derived and Table 5.1 lists and provides details of these atmospheric parameters. Each of these 12 new predictors is discussed in greater detail below.

Table 5.2 contains a matrix showing the cross correlation between all possible pairs of predictors. The Galapagos 200 mb u and v parameters correlate very highly with each other (> 0.8), which suggests that when the u wind is positive (westerly), the v wind also tends to be positive (southerly) and vice-versa. April Atlantic Ocean pressure and January southwest U.S. surface pressure also show modest correlations (~ 0.30). The smallest correlations occur between the July South Indian Ocean 500 mb height and July Coral Sea upper winds. Table 5.3 shows the relationships between the 12 individual hindcast predictors and nine forecast parameters. By comparing Tables 5.2 and 5.3 it is

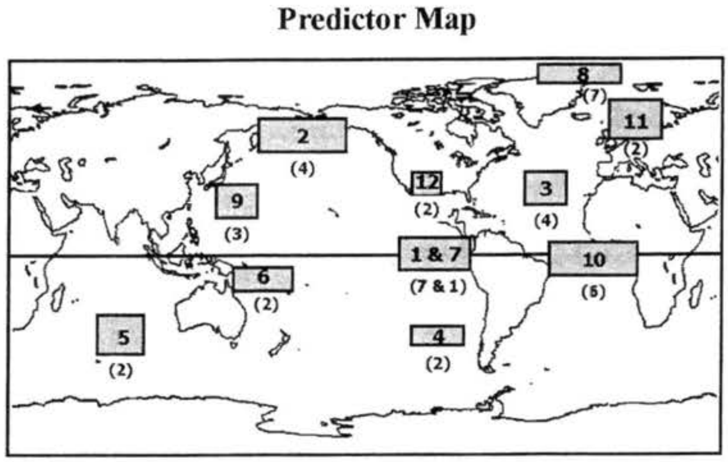

Figure 5.1: Global map showing locations of TC predictors. Table 5.1 provides a listing and description of these predictors. The numbers in the boxes are keyed to descriptions in the bottom of Table 5.1. The numbers in parentheses beneath each box indicate how many predictor equations used each predictor.

Table 5.1: Listing of predictors chosen for each forecast parameter and the total hindcast variance explained by these predictors for the August forecast. The name and atmospheric property utilized in each predictor is given below - where the number for each is keyed to Fig. 5.1. This same list is provided again (for convenience) in Table 4.2, 5.2 and 5.3.

Forecast Parameter	No. of Predictors	Predictors Chosen from Table	Variability Explained by Hindcast (R^2) (1949-1999)	Likely Independent Forecast Skill (Jackknife)
NS	5	3, 6, 7, 9, 11	.55	.41
NSD	5	1, 2, 3, 8, 10	.71	.61
H	4	1, 2, 8, 10	.57	.47
HD	5	3, 4, 8, 9, 19	.69	.59
IH	5	1, 3, 5, 8, 12	.68	.59
IHD	5	1, 4, 5, 6, 9	.78	.72
NTC	5	1, 2, 8, 10, 12	.74	.66
TONS	4	1, 8, 10, 11	.68	.60
TOH	4	1, 2, 8, 10	.64	.56

1) Galapagos July 200 mb v, sign of correlation (-)
2) Bering Sea July SLP, sign of correlation (-)
3) Atlantic Ocean July SLP, sign of correlation (-)
4) SE Pacific July 200 mb u, sign of correlation (-)
5) S. Indian Ocean July 500 mb ht, sign of correlation (-)
6) Coral Sea July 200 mb u, sign of correlation (+)
7) Galapagos July 200 mb u, sign of correlation (-)
8) North Greenland June 200 mb u, sign of correlation (+)
9) Northwest Pacific June SLP, sign of correlation (+)
10) S. Atlantic Ocean April SLP, sign of correlation (-)
11) Scandinavia February SLP, sign of correlation (-)
12) SW USA January SLP, sign of correlation (-)

shown that, in general, the predictors correlate much better with the predictants than with each other. Most other pairs of parameters are correlated at values less than r = 0.3, indicating that these predictors are much less well associated with one another.

Table 5.2: Matrix of the linear cross correlations of 12 predictors in Fig. 5.1. The averages in the lower row are computed from absolute values, hence disregarding sign.

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1)	—	0.10	0.10	0.24	-0.29	0.09	0.82	-0.29	-0.41	-0.15	0.26	0.20
2)	0.10	—	0.25	0.20	0.03	0.00	0.13	-0.14	-0.21	0.02	0.28	0.23
3)	0.10	0.25	—	0.13	0.13	0.22	0.17	-0.09	0.03	0.23	0.18	0.09
4)	0.24	0.20	0.13	—	-0.02	-0.04	0.10	-0.13	0.10	0.06	0.10	0.09
5)	-0.29	0.03	0.13	-0.02	—	0.01	-0.22	0.12	0.12	0.34	-0.03	0.08
6)	0.09	0.00	0.22	-0.04	0.01	—	0.19	0.06	-0.07	-0.16	-0.06	-0.09
7)	0.82	0.13	0.17	-0.10	0.22	0.19	—	-0.27	-0.24	0.03	0.20	0.09
8)	-0.29	-0.14	-0.09	-0.13	0.12	0.06	-0.27	—	0.23	-0.06	-0.21	-0.19
9)	-0.41	-0.21	0.03	0.10	0.12	-0.07	-0.24	0.23	—	0.06	-0.09	-0.30
10)	-0.15	-0.02	0.27	0.06	0.34	-0.16	0.03	-0.06	0.06	—	0.11	0.05
11)	0.26	0.28	0.18	0.10	-0.03	-0.06	0.20	-0.21	-0.09	0.11	—	0.22
12)	0.20	0.23	0.09	0.09	0.08	-0.09	0.09	-0.19	-0.30	0.05	0.22	—
Ave.	0.27	0.14	0.15	0.11	0.13	0.09	0.22	0.16	0.17	0.12	0.16	0.15

1) Galapagos July 200 mb v - sign of correlation (-)
2) Bering Sea July SLP - sign of correlation (-)
3) Atlantic Ocean July SLP - sign of correlation (-)
4) SE Pacific July 200 mb u - sign of correlation (-)
5) S. Indian Ocean July 500 mb ht - sign of correlation (-)
6) Coral Sea July 200 mb u - sign of correlation (+)
7) Galapagos July 200 mb u - sign of correlation (-)
8) North Greenland June 200 mb u - sign of correlation (+)
9) Northwest Pacific June SLP - sign of correlation (+)
10) S. Atlantic Ocean April SLP - sign of correlation (-)
11) Scandinavia February SLP - sign of correlation (-)
12) SW USA January SLP - sign of correlation (-)

Another way to measure the skill of the predictors is to examine the August TC activity in the years associated with the top ten values of each predictor in comparison to August TC activity in the years with the bottom ten values of each predictor. Tropical cyclones were composited for the ten years with the largest and smallest values for each predictor. These two composites of TC activity were computed and put into ratio form as shown in Table 5.4. Note the extremely large differences associated with the Galapagos predictors as well as the Greenland 200 mb u wind and the southwest U.S. January pressure. The weakest relationships are seen for the July South Indian Ocean 500 mb height

Table 5.3: Cross correlation matrix for predictors versus predictants. The average values in the lower row are computed without respect to sign.

Predictor	NS	NSD	H	HD	IH	IHD	NTC	TONS	TOH	Ave.
1)	-0.49	-0.54	-0.39	-0.44	-0.49	-0.48	-0.55	-0.56	-0.47	0.49
2)	-0.31	-0.43	-0.50	-0.40	-0.38	-0.32	-0.44	-0.26	-0.40	0.38
3)	-0.34	-0.44	-0.40	-0.45	-0.41	-0.08	-0.37	-0.25	-0.32	0.33
4)	-0.19	-0.35	-0.30	-0.38	-0.34	-0.45	-0.41	-0.25	-0.32	0.33
5)	-0.08	0.01	0.03	-0.07	-0.24	-0.33	-0.15	0.01	-0.10	0.11
6)	0.18	0.06	0.13	0.02	0.04	0.13	0.11	0.14	0.09	0.10
7)	-0.53	-0.57	-0.42	-0.44	-0.38	-0.33	-0.19	-0.58	-0.50	0.47
8)	0.35	0.43	0.40	0.46	0.48	0.26	0.45	0.42	0.44	0.41
9)	0.30	0.35	0.29	0.41	0.40	0.51	0.47	0.31	0.30	0.37
10)	-0.27	-0.36	-0.34	-0.42	-0.25	-0.23	-0.35	-0.38	-0.42	0.34
11)	-0.39	-0.44	-0.30	-0.35	-0.23	-0.17	-0.33	-0.53	-0.43	0.35
12)	-0.32	-0.35	-0.36	-0.42	-0.47	-0.40	-0.46	-0.37	-0.37	0.39
Ave.	0.31	0.36	0.32	0.36	0.34	0.31	0.38	0.33	0.35	

1) Galapagos July 200 mb v - sign of correlation (-)
2) Bering Sea July SLP - sign of correlation (-)
3) Atlantic Ocean July SLP - sign of correlation (-)
4) SE Pacific July 200 mb u - sign of correlation (-)
5) S. Indian Ocean July 500 mb ht - sign of correlation (-)
6) Coral Sea July 200 mb u - sign of correlation (+)
7) Galapagos July 200 mb u - sign of correlation (-)
8) North Greenland June 200 mb u - sign of correlation (+)
9) Northwest Pacific June SLP - sign of correlation (+)
10) S. Atlantic Ocean April SLP - sign of correlation (-)
11) Scandinavia February SLP - sign of correlation (-)
12) SW USA January SLP - sign of correlation (-)

and April Atlantic pressure. Table 5.5 lists the actual values of the top 10 predictant values divided by bottom 10 from 1949-1999.

Table 5.4: Ratios of tropical cyclone activity parameters during the 10 Augusts with the largest values of each predictor to the values for the 10 Augusts associated with the lowest values for that predictor for 1949-1999.

Predictor	NS	NSD	H	HD	IH	IHD	NTC	TOH	TONS
1) Galapagos July 200 mb v	3.75	7.33	3.30	5.50	4.06	25.60	4.75	2.36	2.69
2) Bering Sea July SLP	2.50	5.33	2.98	3.67	2.87	7.15	1.83	2.63	1.45
3) Atlantic Ocean July SLP	3.27	4.00	4.47	4.00	2.79	2.02	2.20	2.64	1.82
4) SE Pacific July 200 mb u	2.50	2.86	3.32	3.33	2.76	9.91	1.83	1.92	1.48
5) S. Indian Ocean July 500 mb ht	1.03	1.63	1.30	2.25	1.40	2.62	1.06	1.07	0.83
6) Coral Sea July 200 mb u	2.04	3.67	1.87	2.50	2.05	3.29	2.27	2.14	1.94
7) Galapagos July 200 mb u	3.99	9.00	3.79	6.00	3.91	28.00	4.43	2.88	2.60
8) North Greenland June 200 mb u	3.35	6.33	5.11	8.00	3.73	31.50	3.86	2.20	2.00
9) Northwest Pacific June SLP	3.33	3.40	5.87	5.00	3.89	7.78	2.31	2.75	1.95
10) S. Atlantic Ocean April SLP	2.11	2.86	2.90	1.40	1.75	1.49	2.23	1.75	1.48
11) Scandinavia February SLP	2.44	3.14	2.38	2.67	2.20	2.16	2.92	1.77	2.05
12) SW USA January SLP	2.80	4.50	6.57	11.00	4.13	114.00	3.38	2.30	1.67

Table 5.5: The actual hurricane activity values for the 10 most active and least years for each activity parameter and their ratios for 1949-1999.

	NS	NSD	H	HD	IH	IHD	NTC	TOH	TONS
Top 10 seasons	53	272.5	34	154	15	48.5	652.8	29	46
Bottom 10 seasons	8	20.25	2	1.25	0	0	36.25	0	1
Ratio	6.6	13.5	17	123.21	∞	∞	18	∞	46

5.1 Galapagos and Southeast Pacific Predictors

The two most utilized predictors for the August forecast are the July 200 mb u and v winds over the equatorial Pacific just west of South America. The 200 mb u wind indices are derived from the area bounded by 5°S-5°N, 110-85°W, whereas the 200 mb v wind is computed from an area of 4°S-8°N, 105-79°W; these are termed Galapagos 200 mb v (or u). One or the other of these two predictors is involved in all of the TC forecast equations (see Table 5.1) wherein 20-30 percent of August TCs variance is typically explained, depending on the parameter chosen. When these areas experience winds that are anomalously westerly and southerly, TC activity is generally suppressed in the Atlantic basin. The latter condition appears to be linked primarily to ENSO. El

Niño-linked anomalous convection over the eastern Pacific Ocean will produce enhanced upper-level westerly winds over the adjacent Caribbean Sea and western tropical Atlantic Ocean. These westerly winds lead to increased vertical shear of the zonal wind over the main Atlantic TC development region (10-20°N, 60-30°W) and, thereby, diminished TO TC activity (see Fig. 5.2 and Gray 1984b). Shapiro (1987) found that in addition to increased vertical shear, El Niño events produced strong anticyclonic vorticity anomalies in the low-level winds of the tropical Atlantic which is also an unfavorable situation for tropical cyclogenesis.

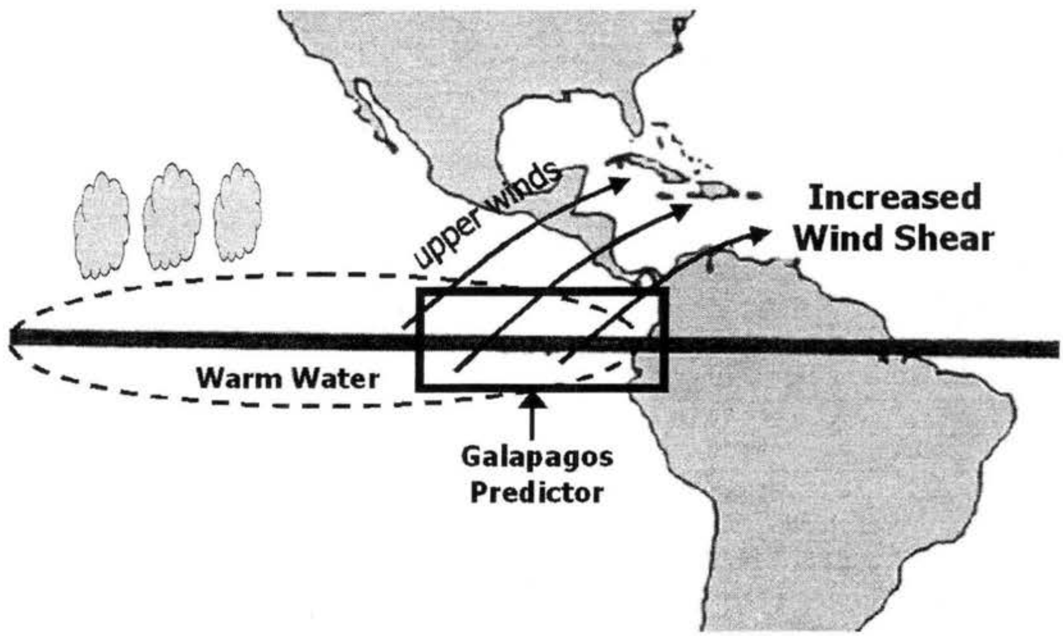

Figure 5.2: Simplified conceptual rendering of El Niño's effect on Atlantic TCs

However, El Niño is not the only climate factor that affects the two "Galapagos" predictor values. There appears to be a notable influence from the Southern Hemisphere (SH) winter longwave pattern. Occasionally it is observed that deep SH troughs will extend to near the equator, creating strong upper westerly winds in both the tropical Atlantic and Pacific. These deep intrusions from the SH high latitudes which appear to be independent of the state of ENSO, tend to be short-lived (on the order of 5-10 days) but can radically change the prevailing 200 mb wind patterns and significantly alter u and v flow anomalies (Fig. 5.3).

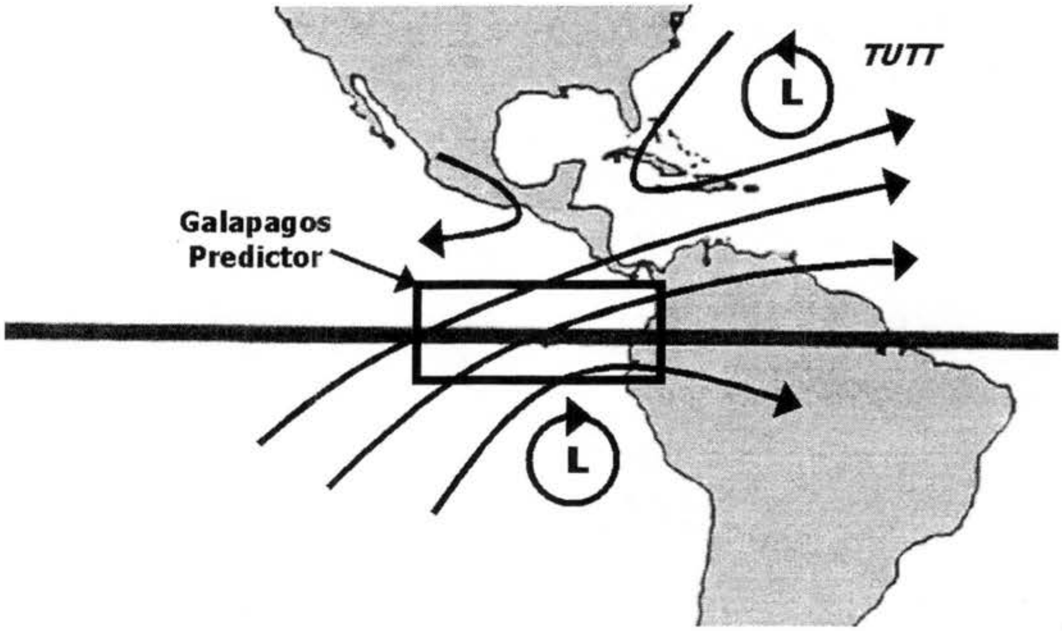

Figure 5.3: As in Fig. 5.2 but for the July 200 mb pattern typically seen before an inactive August with a Southern Hemisphere trough.

During July prior to an active August, it is generally observed that the SH upper-level westerly winds are at higher latitudes, leaving a strong anticyclone over northern South America. This upper-high is characterized by easterly wind anomalies near the equator extending from the eastern coast of north Brazil westward to 120°W with northerly anomalies off the west coast of Ecuador, as shown in Fig. 5.4. Such a pattern is quite favorable for Atlantic tropical-only TC genesis in a concurrent and predictive sense as it is associated with weak zonal wind shear and easterly 200 mb wind anomalies across the tropical Atlantic, often extending from northern South America to the Greenwich Meridian. It is hypothesized that conditions promoting the appearance and maintenance of this state of the atmosphere during July are a precursor signal to an active August. If this pattern recurs in August when the background climatology has become increasing favorable for TC formation, it often leads to a very active month.

Another plausible physical association concerns the Madden-Julian Oscillation (MJO). Though MJO signals appear in zonal winds at both 850 and 200 mb, the 850 mb component of the oscillation tends to be blocked by the Andes Mountains while the 200 mb influence can freely traverse the globe. Hence, when 200 mb zonal winds in the Eastern

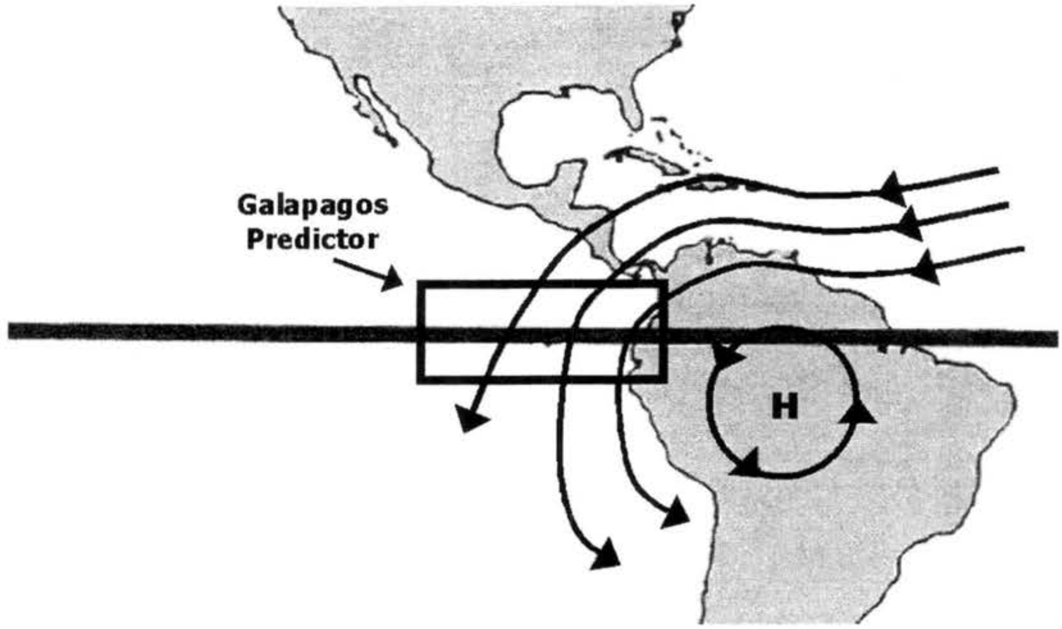

Figure 5.4: As in Fig. 5.3 but for the July 200 mb pattern typically observed before active Augusts.

Pacific Ocean are more westerly than normal, it may be evidence that an inactive phase of the MJO is beginning to affect convection in the tropical Atlantic. Another interpretation is that the more time the MJO spends in an unfavorable (westerly) state in the Atlantic during July, the more time it will likely spend in a favorable (easterly) mode during August owing to the approximate 30-50 day period of the MJO. This relationship deserves further study.

Yet another predictor which is somewhat related to the equatorial winds is the southern midlatitude July 200 mb u wind west of Chile (40-35°S, 110-85°W) (Region 4 in Fig. 5.1). When these upper-level westerly winds are weaker than normal the duration of Atlantic TCs is typically increased. Broadscale Atlantic TC activity is greater if the 200 mb winds in the "Galapagos" region are anomalously strong from the east (Region 7 of Fig. 5.1), 200 mb winds at 15-25°S are strong from the west (off the west coast of South America) and SH midlatitude winds (30-40°S, same longitude of Region 4 of Fig. 5.1) are anomalously easterly. This predictor configuration may be a reflection of the extent of SH mid-latitude westerly flow impinging deeper into the tropics. If weaker SH westerly winds occur in June-July, there is usually a greater level of August TC activity. Although the equatorial 200 mb wind is moderately positively correlated with the mid-latitude flow (r = 0.25), using this mid-latitude flow in combination with the equatorial wind significantly increases the amount of variance explained in HD, IHD and NTC.

5.2 Atlantic SLPA Predictors

Two Atlantic Ocean SLPA areas are used as predictors. The most significant of these involves the July SLPA in the central Atlantic (25-37.5°N, 47.5-25°W; Region 3 in Fig. 5.1). This domain is notably different from the area utilized by the Gray et al. (1993) forecast scheme which uses SLPA in the Caribbean Sea region. It is not known why lower pressure in the subtropical Atlantic during July favors August TC activity. Lower pressure in the deep tropical Atlantic in July favor both September and October activity. Thus, in the central Atlantic, if the July subtropical SLPA is low then (typically) August SLPA is low, as well. In general, low early season pressure in the Atlantic correlates well with increased Atlantic basin seasonal and monthly TC activity. It has been known since the mid-1930s (Brennan 1935, Ray 1935) that anomalous low pressure is indicative of weak midtroposphere subsidence and less drying of the mid-atmosphere. Low pressure in the Atlantic Ocean is also associated with reduced trade winds which, in turn, is linked to warmer SSTs, at least in part as a consequence of decreased evaporation and upwelling.

April SLPA in the equatorial Atlantic (10°S-5°N, 35°W-15°E) also displays a strong inverse relationship with August TC activity, especially activity in the deep tropics on both monthly (i.e., August) and seasonal time scales. Figure 5.5 shows all early seasonal predictors used in the forecast scheme. It appears that April SLPA may be better linked with total seasonal TC variability than concurrent August SLPA. Generally, if the April pressure in the equatorial Atlantic (Region 10 of Fig. 5.5) is lower than normal, then lower August SLPA and negative ZWA values are typically observed in the tropical Atlantic. This April SLPA index is also linked to ENSO where in July SSTAs in Niño 4 correlate at r = 0.3 with this April index.

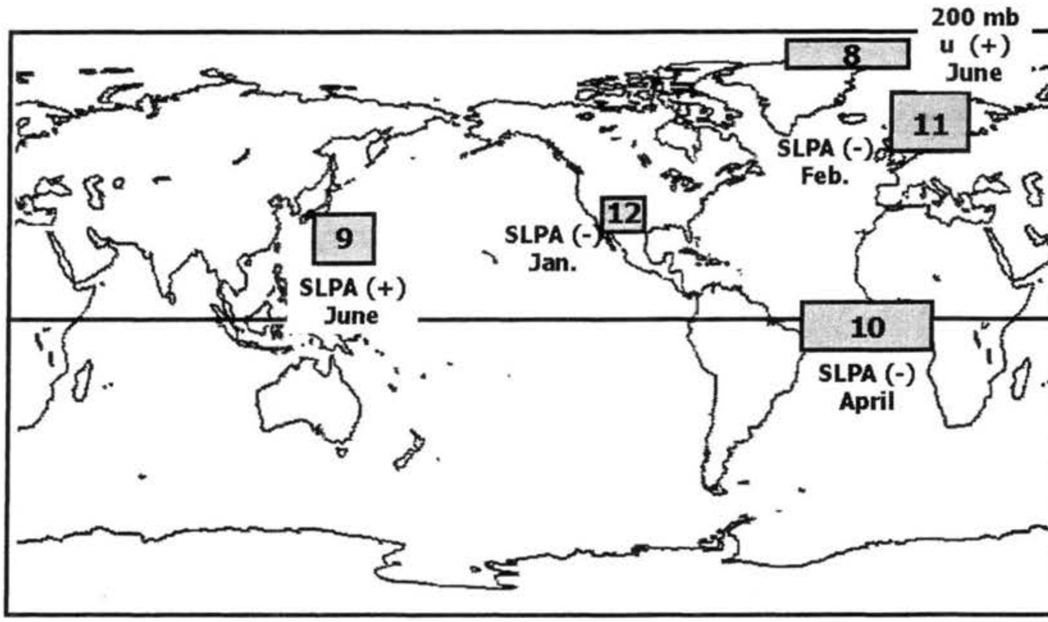

Figure 5.5: Summary of early season predictors which occur before June 1. The sign (+ or -) of their correlation association with August TC activity is in parentheses.

5.3 Greenland Predictor

Another predictor from the Atlantic region is the June 200 mb zonal wind centered over the far northern region of Greenland (80-85°N, 45°W-10°E, Region 8 of Fig. 5.5). When the June 200 mb wind in this area is anomalously strong from the west, August TC activity is enhanced. Though somewhat peculiar, this connection possibly reflects mid-latitude blocking conditions near Greenland and, hence, the phase of the North Atlantic Oscillation (NAO). The NAO is defined for this paper as the pressure difference between Portugal and (Minus) Iceland with positive/negative values indicating increased/decreased mid-latitude zonal winds over the North Atlantic. Enhanced ridging attending a negative NAO leads to easterly upper-wind anomalies over northern mid-latitudes while westerly anomalies occur over the polar latitudes as shown in Fig. 5.6. Van Loon and Rogers (1978) observed that enhanced wintertime blocking was more prevalent over the North Atlantic during the decades of the 50s and 60s than during the 1970s and 1980s. As TC activity during the 50s and 60s was much greater than during the 70s and 80s, it is hypothesized that the enhanced wintertime blocking patterns (implicit as westerly anomalies for the

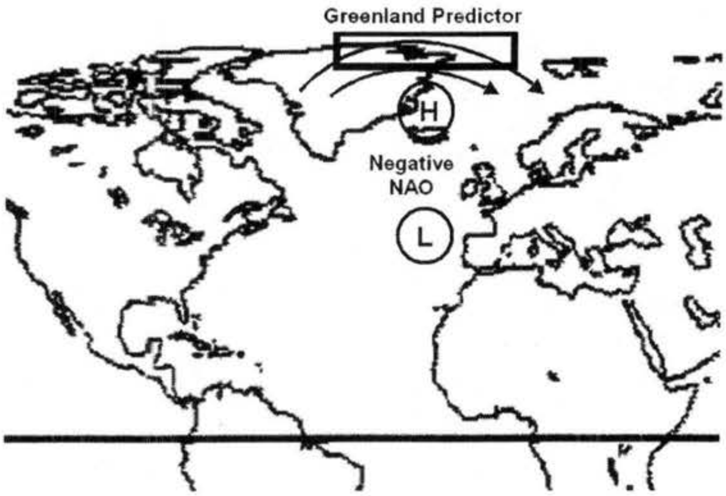

Figure 5.6: Conceptual schematic summarizing the key aspects of the June 200 mb geopotential height pattern that typically favors increased August TC activity.

Greenland 200 mb zonal wind) are thus a harbinger of active hurricane seasons. During the past six years (1995-2000), winter circulations have reverted to the enhanced blocking patterns reminiscent of the 50s and 60s and correlate well with the recent six years of more active seasonal and August Atlantic TC activity.

5.4 Northwest Pacific Predictors

The Pacific region also holds some key predictors for August TC genesis. One of these concerns June SLPA in the northwest Pacific Ocean (18-30°N, 134-154°E), southeast of Japan (Region 9 of Fig. 5.5). When June pressure anomalies in this region are high, August TC activity tends to be increased in the Atlantic basin. We suspect that this predictor is linked to an observed tendency for significant reduction of TC activity in the northwest Pacific basin during June prior to active TC seasons in the Atlantic. In particular, El Niño events are associated with low pressure in this region as well as to fewer Atlantic TCs and to slightly enhanced northwest Pacific TC activity. This predictor is most closely linked to August IHD and HD as it explains about 20-25 percent of the variance of these two parameters.

Surface pressure anomalies over the Bering Sea region (47-62°N, 156°E-164°W – Region 2 of Fig. 5.1) during July are also strongly correlated with August Atlantic TC activity. There is more Atlantic TC activity when July pressure in this region is low. One of these two Pacific Ocean SLPA indicators (i.e., either June Region 9 or July Region 2) is selected by every forecast equation (except for TONS). The latter shows the importance of early summer conditions in the Pacific Ocean for August Atlantic TC activity and emphasizes the linkages between Atlantic TC activity and the global circulation. Figure 5.7 shows all July predictors.

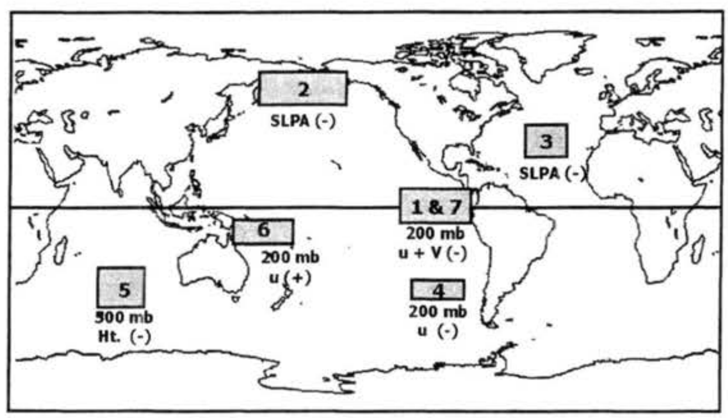

Figure 5.7: Summary illustration of July predictors used in the August forecast scheme showing sign of the correlation of each with August TC activity in parentheses.

These Pacific region predictors suggest that important large-scale differences occur over the Pacific Ocean during summers prior to active versus inactive Augusts in the Atlantic basin. An idealized look at global features associated with an active pattern is shown in Fig. 5.8. In general, increased August Atlantic basin activity follows anomalous low pressure in the midlatitudes of the western Pacific Ocean and high pressure in the west tropical Pacific during the early summer. An effect of this pressure pattern is that vertical shear of the zonal wind is typically greater in the tropical northwest Pacific Ocean during summers before active Atlantic years. This shear is greater than normal due to increased 200 mb westerly winds and 850 mb easterly winds, similar to what occurs during a La Niña event.

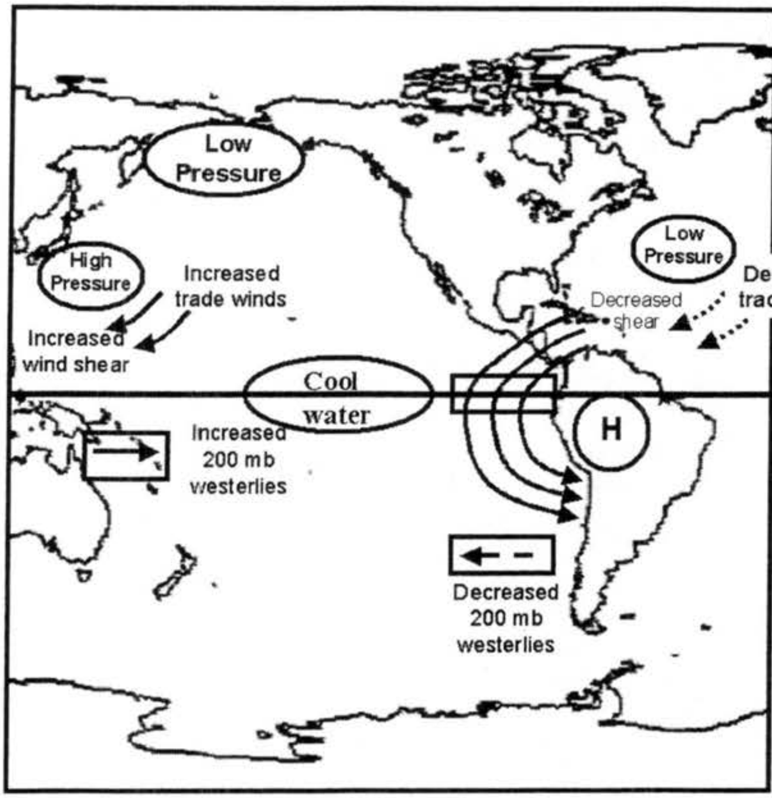

Figure 5.8: Simplified conceptual summary of the key features in an idealized summer pattern prior to increased August TC activity.

It is notable that a reverse (from the Pacific) synoptic-scale pattern is typically observed in the Atlantic Ocean in the early summer before an active August (Fig. 5.8). In particular, anomalous low pressure is noted in the Atlantic tropics with a diminished Bermuda high and slightly increased seasonal high pressure in higher latitudes. These lower pressures in the Atlantic subtropical high are usually accompanied by low vertical wind shear in the main TC development region with reduced trade winds and more easterly upper-level flow.

5.5 Southwest Pacific Predictors

Another significant change related to August Atlantic TC activity also occurs in the SH (winter) during July. In this instance, an index of 500 mb heights in the Southern

Indian Ocean (SIO) (42.5-27.5°S, 72.5-95°E – Region 5 in Fig. 5.7) is used as a predictor for IH and IHD. A weaker-than-normal ridge in the SIO is favorable for August TC activity in the Atlantic basin. The physical mechanism(s) for this relationship are not clear at present but may be linked to processes altering August ZWA-linked shear conditions across the eastern Atlantic. In this case, lower heights in the SIO are well correlated with easterly 200 mb wind anomalies across the main Atlantic TC development region as shown in Fig. 5.9. An enlargement of the African portion of Fig. 5.9 is shown in Fig. 5.10. Negative (easterly) 200 mb ZWA anomalies are best associated with the formation of IH and IHD while H and NS genesis often show little relationship with upper-level winds in the far eastern Atlantic. These conditions suggest that shear is the dominant operative factor in this situation.

Another predictor for August TC activity found in the SH is the July 200 mb u wind in the general vicinity of the Coral Sea (17.5-7.5°S, 145-180°E). When winds in this domain are enhanced from the west, Atlantic TC formation tends to be increased during the subsequent August. This predictor is also well-correlated with ENSO, especially region Niño 3.4 in the central Pacific as well as with increased zonal shear in the western Pacific. Anomalous westerly Coral Sea winds are closely tied to high pressure in the tropical central and eastern Pacific, as well as to cool water conditions in Niño 3.4 during August (hence La Niña).

Additional TC predictors (discussed previously) were found based on climate conditions much earlier in the year during the NH winter (see Fig. 5.5). These include January surface pressure over the Southwest USA (30-40°N, 110-95°W Region 12 of Fig. 5.5) and February surface pressure over Scandinavia (52.5-75°N, 5°W-35°E – Region 11 of Fig. 5.5), both of which are negatively correlated with subsequent TC activity. The January SW U.S. pressure is selected for predicting a few TC indices, while the February Scandinavian pressure parameter is utilized primarily with the TO indices. Low February surface pressure in Scandinavia appears to be related to enhanced August TC activity through its association with stronger mid-latitude blocking over Greenland. North Atlantic enhanced blocking, and hence, higher pressure near Greenland, is linked to a low pressure trough in the vicinity of Scandinavia.

The relationship between lower January pressure over the southwest United States and enhanced August TC activity is difficult to explain but could occur as a combination of effects attending cold ENSO and cold PDO patterns. Despite the lack of an obvious physical linkage, this January southwest SLPA association is very robust (Table 5.3) and needs to be explored further. The forecasts for August-only activity parameters were very useful for refining the Gray seasonal forecast. In addition, the August NTC forecast has a strong relationship with August landfalling TCs. These associations are covered in Chapter 6.

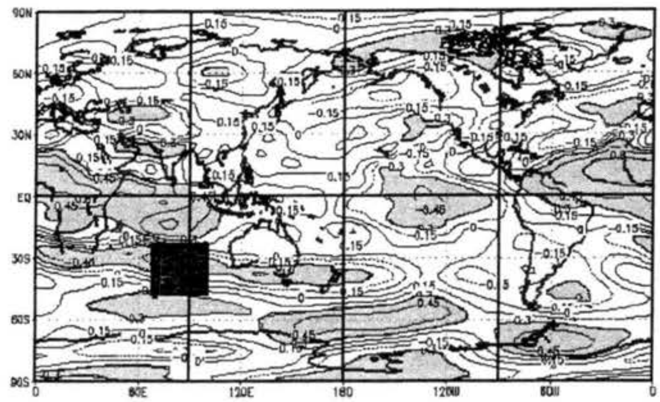

Figure 5.9: Analysis of correlation between July South Indian Ocean 500 mb ridge conditions (in the shaded box) and August 200 mb ZWA. Note strong positive correlations over the tropical Atlantic and Africa. An enlargement of this area is shown in Fig. 5.10.

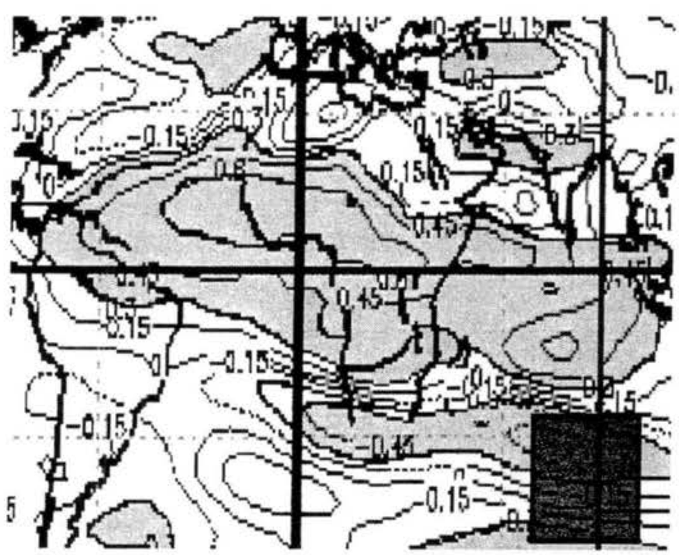

Figure 5.10: Closer look at the portion of Fig. 5.9 showing details of the strong correlation area extending out of the South Indian Ocean, across Africa and the tropical Atlantic. Positive SIO ridge values in July are well correlated with high August ZWA values in the tropical Atlantic.

Chapter 6

APPLICATIONS OF THE AUGUST FORECAST

The best possible application of a new forecast technique is in successful operational testing with new data. However, we have found another application of the August-only forecast scheme which is to combine it with the Gray 1 August statistical forecast (Gray et al. 1997) to make better seasonal predictions using a simple linear regression model. This exercise is useful because the August-only forecast correlates at r = +0.68 with seasonal activity, explaining about 46 percent of the variance. We also consider applying August-only forecasting techniques to August-only landfall activity and in developing analog forecast techniques for August activity. Thee chapter ends with a detailed review of the results for two years of (independent) test forecasts of August activity for 2000 and 2001.

6.1 The August Forecast as a Seasonal Predictor

One approach to using the August-only forecast as a seasonal predictor starts with the Gray et al. (1997) 1 August forecast and adjusts it up or down based on the August-only forecast. This is done by simply combining an approximately 70 percent weighting of the Gray et al. (1997) forecast with a 30 percent weighting of the August-only forecast. Table 6.1 shows the increases in hindcast skill and the new forecast errors (i.e., residuals) for seasonal NTC from 1950-1999 with and without the combination with the August-only forecast. The Gray 1 August statistical forecast explains about 59 percent of the seasonal variance of NTC. However, in combination with the August-only forecast, the hindcast skill increases to 69 percent.

Table 6.1: Comparative summary of observed NTC versus various Gray 1 August seasonal NTC forecast (1997), the August-only NTC hindcast and old and new forecast residuals. The average values of the residuals are expressed as absolute numbers.

Year	Seasonal NTC after Aug 1	Aug NTC Fcst.	Gray et al. after 1 Aug Fcst	New Gray et al. after 1 Aug Fcst	Old Residual	New Residual
1950	237	62.9	149	160.4	-88.0	-76.6
1951	108	32.0	106	102.4	-2.0	-5.6
1952	93	26.2	154	128.2	61.0	35.2
1953	113	18.9	119	98.2	6.0	-14.8
1954	116	3.0	119	82.9	3.0	-33.1
1955	192	68.1	163	174.5	-29.0	-17.5
1956	60	31.8	137	122.5	77.0	62.5
1957	66	6.5	88	66.0	22.0	0.0
1958	135	67.3	141	159.3	6.0	24.3
1959	74	11.6	69	58.5	-5.0	-15.5
1960	82	7.6	100	74.9	18.0	-7.1
1961	209	10.4	189	135.8	-20.0	-73.2
1962	33	13.4	77	65.5	44.0	32.5
1963	115	40.9	123	122.1	8.0	7.1
1964	159	40.7	162	147.4	3.0	-11.6
1965	82	4.8	42	34.3	-40.0	-47.7
1966	95	31.1	160	136.8	65.0	41.8
1967	96	5.1	65	49.6	-31.0	-46.4
1968	24	8.2	5	13.4	-19.0	-10.6
1969	150	30.5	250	195.1	100.0	45.1
1970	55	29.3	81	83.4	26.0	28.4
1971	91	16.1	115	92.9	24.0	1.9
1972	20	14.7	38	41.2	18.0	21.2
1973	43	13.4	86	71.4	43.0	28.4
1974	75	24.3	84	80.5	9.0	5.5
1975	81	34.5	93	96.3	12.0	15.3
1976	81	38.9	75	88.7	-6.0	7.7
1977	46	5.3	45	36.7	-1.0	-9.3
1978	83	23.0	86	80.7	3.0	-2.3
1979	84	40.9	63	82.8	-21.0	-1.2
1980	134	53.8	137	143.7	3.0	9.7
1981	108	17.4	138	109.2	30.0	1.2
1982	31	6.4	40	34.5	9.0	3.5
1983	31	23.0	29	43.3	-2.0	12.3
1984	77	13.5	67	59.1	-10.0	-17.9
1985	100	13.2	96	77.7	-4.0	-22.3
1986	29	15.9	65	60.0	36.0	31.0
1987	47	24.0	47	56.1	0.0	9.1
1988	122	11.3	125	94.8	3.0	-27.2
1989	124	31.5	127	115.6	3.0	-8.4
1990	89	52.0	142	145.2	53.0	56.2
1991	56	27.6	70	74.6	14.0	18.6
1992	66	36.2	62	77.7	-4.0	11.7
1993	51	25.9	54	62.4	3.0	11.4
1994	34	8.6	45	39.9	11.0	5.9
1995	205	64.4	166	172.9	-39.0	-32.1
1996	169	50.9	204	184.7	35.0	15.7
1997	35	4.1	89	64.3	54.0	29.3
1998	170	57.8	110	129.9	-60.0	-40.1
1999	193	55.7	129.5	140.6	-63.5	-52.4
Ave	95.4	26.4	102.5	95.4	24.9	22.9

The largest seasonal hindcast skill improvements with this approach included the hindcast of NSD for which the amount of variance explained increased by fifteen percent. Table 6.2 shows all TC parameters and the improvement realized when after the August-only forecast is utilized in the statistical prediction. The seasonal hindcast of IHD was least affected by this August forecast, rising only four percent in covariance explained.

Table 6.2: Summary of mprovements of seasonal forecast of six parameters by including August forecast indices. The seasonal forecast parameters are listed in the left column and the August-only factors utilized for each are listed in the right column.

Forecast Parameter	Gray August Hindcast Skill (R^2) 1950–1999	Including August-only Hindcast	Forecast Equation Combined
NS	.44	.57	NS
NSD	.52	.67	NS
H	.47	.59	NTC
HD	.50	.64	NTC
IH	.52	.64	IH
IHD	.43	.47	IHD
NTC	.59	.69	NTC

6.2 August Landfall Relationships

As discussed in Chapter 2, a strong relationship exists between August NTC and the number of August tropical systems landfalling on the U.S. coastline. Tables 6.3 and 6.4 detail this relationship in bold for the years 1949-1999 divided into 15 and 26 year subsections. The relationships are strongest for the more intense (IH) systems. Six times as many hurricanes came ashore during the 26 most active seasons (Table 6.4) as during inactive ones, and no IH made landfall during the 15 seasons with the least August NTC (Table 6.3). It is important to note that these relationships were very similar for hindcast August NTC as is also shown in Tables 6.3 and 6.4. Note in Table 6.4 the large 3 to 1 difference in landfalling H with an even stronger (4 to 1) relationship for IH. Figures 6.1 and 6.2 compare the H and IH landfalls in the observed versus hindcast NTC values for 26 and 15 year periods, respectively. These strong landfall contrasts between high and low NTC values allow for the development of landfall probability forecasts based on forecast NTC.

In any given year, there is only a small chance of either a H or IH making landfall on the U.S. coast during August. Table 6.5 summarizes the average probabilities for one or more TCs affecting the US. Note that the sum of these probabilities is less than 100 percent as several instances of multiple NS and H have occurred. These basic probabilities can be adjusted based upon the forecast NTC for August using historical relationships of strike probability.

Table 6.3: Comparison of numbers and ratios for observed versus hindcast August landfall events by intensity class during the 15 largest versus the 15 smallest August values of NTC from 1949-1999.

	Named Storms	Hurricanes	Intense Hurricanes
Largest 15 Years Observed NTC	17	12	5
Largest 15 Years Hindcast NTC	15	10	4
Smallest 15 Years Observed NTC	6	1	0
Smallest 15 Years Hindcast NTC	6	2	1
Ratio of Largest/Smallest Observed	2.8	12.0	∞
Ratio of Largest/Smallest Hindcast	2.5	5.0	4.0

Table 6.4: Comparison of numbers and ratios for observed versus hindcast August landfall events by intensity class during the 26 largest versus the 26 smallest August values of NTC from 1949-2000.

	Named Storms	Hurricanes	Intense Hurricanes
Largest 26 Years Observed NTC	23	17	8
Largest 26 Years Hindcast NTC	24	18	8
Smallest 26 Years Observed NTC	16	6	2
Smallest 26 Years Hindcast NTC	15	5	2
Ratio of Largest/Smallest Observed	1.6	2.8	4.0
Ratio of Largest/Smallest Hindcast	1.6	3.6	4.0

Table 6.5: Probability of one or more U.S. landfalling TC(s) during August.

Type	Probability
Tropical Storm	55%
Hurricane	41%
Intense Hurricane	10%

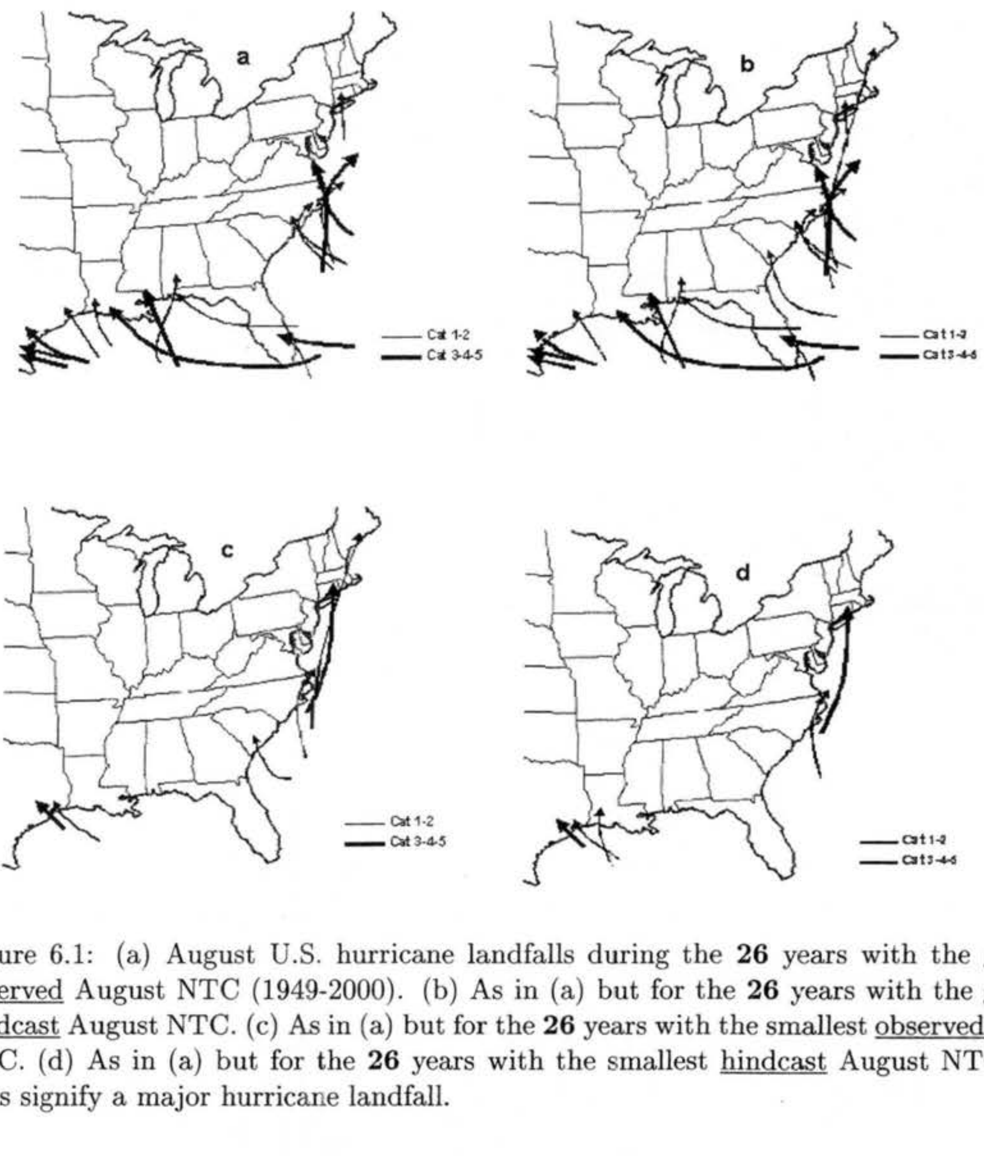

Figure 6.1: (a) August U.S. hurricane landfalls during the **26** years with the greatest observed August NTC (1949-2000). (b) As in (a) but for the **26** years with the greatest hindcast August NTC. (c) As in (a) but for the **26** years with the smallest observed August NTC. (d) As in (a) but for the **26** years with the smallest hindcast August NTC. Bold lines signify a major hurricane landfall.

Figure 6.2: a) August U.S. hurricane landfalls during the **15** years with the greatest observed August NTC (1949-2000). (b) As in (a) but for the **15** years with the greatest hindcast August NTC. (c) As in (a) but for the **15** years with the smallest observed August NTC. (d) As in (a) but for the **15** years with the smallest hindcast August NTC. Bold lines signify a major hurricane landfall.

6.3 Analog Year Techniques

A variety of analog techniques have been developed to supplement the August statistical forecast. The first analog method consists of simple comparisons of the current August NTC forecast and the previously forecasted August NTC from 1949-1999. Following the approach of the Gray seasonal forecast, four to six (or more) years from the past which most closely match the current year NTC forecast are composited and the characteristics of this composite are compared with the general climate conditions during the first half (pre-August) of the forecast year. Since the analog technique is not independent of the statistical forecast, the forecast numbers are generally quite close. However, in certain years, forecast NTC can be quite different than actual NTC. If the forecast NTC for the analog years is significantly different from the actual NTC, this is likely important and should be used to make qualitative adjustments to the forecast.

Currently, the selection of analog years is based on a number of largely subjective criteria. These include qualitative attempts to visually match the current global conditions with prior years while focusing on the general global July surface pressure pattern, SSTs in the tropical Atlantic and western North Pacific and the 200 mb wind anomalies across the Galapagos region. Another method takes exact July predictor values for the current year and matches the five closest values in the 1949-1999 hindcast data base. A more objective system of choosing analogs is being developed by Philip Klotzbach of the Gray research project at Colorado State University.

6.4 Test Forecasts for August 2000 and 2001

A forecast scheme that lacks true skill will typically do well in hindcasting but show no skill in real time. One of the few methods for diagnosing true forecast skill is to analyze the real-time performance of a technique. A complete diagnostic evaluation of two years of August TC forecasts is presented in this chapter. It is acknowledged that two years of forecasts are insufficient to determine forecast skill conclusively, but it may provide some useful insights into the future skill of the model.

Monthly forecasts for August of 2000 and 2001 were issued at the beginning of August of these two years and discussed in the August seasonal forecast update produced by Gray et al. (2000 2001). The August forecasts included statistical and analog forecasts and a final adjusted forecast based upon input from both sources. The past two years can be considered completely independent from the 1949-1999 developmental data base and are thus a useful test of forecast skill. It is important to note that these forecasts were issued during the development of these statistical forecast schemes. The statistical forecast technique utilized for the issuance of the 2000 and 2001 forecast (labeled "Experimental Statistical Forecast") has been changed. The final forecast scheme which was developed with the same 1949-1999 database (no input from 2000 or 2001) but was not available at the time is shown in Table 6.6 as "Final Statistical Forecast."

Table 6.6: Experimental August 2000 forecast, new August 2000 forecast, final adjusted forecast, and observed August 2000 activity.

Forecast Parameter	Experimental Statistical Forecast	Final Statistical Forecast	Final Adjusted Forecast	Actual Activity
NS	2.29	4.02	3	4
NSD	14.21	20.32	14.25	24.75
H	1.77	2.29	2	2
HD	8.27	9.21	8.25	14
IH	1.13	0.80	1	1
IHD	1.04	1.09	1.25	1
NTC	32.2	37.3	33.0	42.6

Even during the development stage the forecasts verified reasonably well. Table 6.6 shows the 2000 statistical forecasts along with the adjusted forecast and observed data. The final forecast issued for August 2000 was very good. Pressure and zonal wind anomalies over the deep tropics were only slightly below normal yet this season saw the formation of two TOH during August which, as noted previously, generally indicates that an active season is likely (see Table 2.9 and related text for details). Indeed, seasonal NTC for 2000 was 134 percent of normal. All forecasts in Table 6.6 indicated an above average August for all parameters except IHD and verified quite well. Table 6.7 shows the analog years selected for 2000 which were also in good agreement with the final result.

Table 6.7: Tropical cyclone activity parameters for six analog years selected for August 2000 forecast versus the final forecast and observed data.

Year	NS	NSD	H	HD	IH	IHD	NTC
1949	3	15	2	7.5	1	.75	31.9
1951	3	10.75	1	7.25	1	1.75	30.9
1954	2	7.75	1	5	0	0	12.3
1963	2	13.75	2	10.5	1	0.5	30.9
1980	3	19.50	3	13	1	6.5	60.6
1981	2	11	1	0.5	0	0	10.7
Analog Average	2.5	13	1.7	7.25	0.7	1.5	29.6
2000 August Forecast	3	14.25	2	8.25	1	1.25	33
2000 August Observed	4	24.75	2	14.00	1	1	42.6

However, the 2000 forecast had fairly large errors for NSD and HD which were in part due to a single storm, the very anomalously persistent Hurricane Alberto, the longest-lasting Atlantic TC on record for August. Some of the associated error may be linked to the absence of similar cases in the predictor data base expressing the full range of independent possibilities. In other years, when conditions include strong trends that are very similar to past years, the analog forecast should perform quite well, perhaps better than the skill of the hindcast scheme. It is of interest that the newer statistical scheme better accounted for the large number of NSD and HD than the old technique though no data from either 2000 or 2001 was included in the final forecast equations.

The forecast for August 2001 projected below average activity (Table 6.8) despite a seasonal forecast which called for above average seasonal activity. Generally, when seasonal activity is above average, August activity is also enhanced. However, the August 2001 forecast was correct wherein August TC activity was much below normal whereas as seasonal activity was above average. Surface pressures during August over the Atlantic basin were very high and easterly African waves had trouble organizing in the deep tropics. Even though no hurricanes occurred, the three TCs that did form all attained 60 knot winds, which is just below hurricane threshold. The main disagreement between observed activity and the August forecast concerned whether an IH would occur during the month; the statistical models suggested there would be an intense hurricane while the analog analysis indicated only a small chance. This difference was the main cause of the error in the NTC portion of the final August 2001 forecast.

Another problem encountered in the statistical forecasts concerned forecasts of negative HD. This result had occurred only a few times in the hindcast data base while in general indcating that August was going to be inactive with less than 3 HD. The final NSD and HD forecasts taken from the analysis of analog years are shown in Table 6.9. The analog year composite was actually a better forecast than was the final forecast. As there were no hurricanes observed in August 2001, the HD forecast was too high though the predicted NSD was close to observed. However, if just one of the 60 knot named storms had become a hurricane, it is doubtful it would have lasted long enough to help verify the higher HD forecast.

Table 6.8: August 2001 forecast and observed activity.

Forecast Parameter	Experimental Statistical Forecast	New Statistical Forecast	Final Adjusted Forecast Numbers	Actual Activity
NS	1.60	1.79	3	3
NSD	-1.66	9.24	7	11.75
H	0.62	1.61	1	0
HD	-1.09	1.04	2.5	0
IH	0.77	0.23	1	0
IHD	0.59	0.63	0.5	0
NTC	12.6	15.8	21.8	9.5

Table 6.9: Tropical cyclone activity parameters for five analog years selected for August 2001 forecast versus the final forecast and observed data.

Year	NS	NSD	H	HD	IH	IHD	NTC
1953	3	9.5	1	3.5	0	0	14.0
1960	2	4.5	1	1.75	0	0	9.2
1965	2	8.0	2	5.0	0	0	15.7
1970	3	8.5	1	2.25	1	0.5	22.1
1978	4	6.50	2	1.50	0	0	16.2
Analog Average	2.8	7.4	1.4	2.8	0.2	0.1	15.4
2001 August Forecast	3	7.00	1	2.5	1	0.5	21.8
2001 August Observed	3	11.75	0	0	0	0	9.5

The overall results for 2000 and 2001 test forecasts are very promising with indications of true forecasting skill. The statistical model is a useful guide for forecasting August monthly TC activity with additional useful guidance garnered from the analog analyses. Further understanding of the underlying physical processes will lead to better forecasts, especially when extreme and unusual circumstances present themselves.

Chapter 7

CONCLUSIONS AND FUTURE WORK

Extended-range seasonal TC forecasting began 19 years ago with the discovery that two Atlantic basin TC modulators - the state of ENSO and the QBO - in combination with SLPA over the Caribbean Sea could be used to make skillful forecasts (Gray 1984a). Other factors have been added into various seasonal forecast schemes through the years as greater insight and longer, more detailed records of atmospheric conditions became available. The feasibility of a monthly TC forecast was not considered until the past five years when the availability of new datasets and analytical tools made provisional assessments of such studies relatively simple. The new tools and data included global atmospheric and oceanic analyses that became available with the onset of the NCEP/NCAR Reanalysis Project. This and similar data sets were absolutely crucial in developing the current August forecast scheme and has provided insight into the global nature of TC forecasts.

Hindcast results using the reanalysis dataset make a strong case for true skill in future forecasts using this hindcast information. As noted earlier, August-only hindcast skill exceeds current seasonal hindcast skill, an unexpected result. Rather, this type of shorter-term prediction was expected to be less reliable than a more expansive forecast for the entire season (Gray, personal communication) where active and inactive multi-week periods tend to average out. Conversely, a forecast that extends only one month into the future versus three-plus months for the August 1 seasonal forecast is less vulnerable to effects of short-term climate "drift" away from the conditions diagnosed at the beginning of the target month. Regardless, these results suggest that TC activity in other months can also be forecast in a similar manner, and project member, Philip Klotzbach, is developing a similar September-only forecast based on July or earlier data. It may be possible to eventually forecast total seasonal activity as the aggregate combination of three monthly forecasts of August, September, and October which typically comprise about ninety percent of the total Atlantic basin seasonal activity.

Persistent variations in broadscale, global circulation features create precursor signals for August TC activity in the Atlantic basin. Anomalous early-summer high pressure over the northwestern Pacific Ocean, low pressure in the Bering Sea and the subtropical Atlantic Ocean, and 200 mb winds near the Galapagos that are anomalously from the northeast quadrant are all indicative of an active August in the Atlantic (Fig. 5.8). Additional signs which occur much earlier in the year include low pressure in the southwest U.S. in January, reduced pressure over Scandinavia in February and low equatorial pressure in the central Atlantic in April (Fig. 5.5). For some of these relationships, mechanisms linking TCs and the associated conditions are not immediately obvious, and further research is needed to gain better insights into why these physical relationships act as precursor signals.

The study has also revealed some useful parameters for forecasting the post 1 September TC activity. The number of August TOH is closely related to total seasonal activity. Generally, if two or more August hurricanes occur in the deep tropics, then the entire season is likely to be more active than normal (Table 2.10). This association is surprising because the long-term average values for August TOH is only one. The addition of just one August H above the mean reveals considerable information about the likely TC activity for the remainder of the season so that a large number of August TOH is useful as a predictor for activity during the remainder of the season.

An additional application of the August forecast for improving the total seasonal activity forecast. If the August forecast is used as a potential predictor in the Gray statistical seasonal forecast, hindcast variance explained increases (for most parameters) by ten to fifteen percent. This new observation will be utilized in the coming seasonal forecasts and should enhance the long-term skill.

Clearly much additional study is needed to fully verify the nature (even the reality) of some of the predictive relationships currently being utilized in this August-only forecast. For the present we cite Gray (2002, personal communication) concerning this issue:

> "Chapter 5 attempted to give some physical basis for the predictive relationships described here. Some will undoubtedly question the plausibility of some or many of these physical relationships and hold the view that monthly or seasonal forecasts should not be made until the physics behind such correlations is fully understood. We disagree. It is not necessary to completely understand the physics of an association behind variations to utilize it. This monthly forecast research was designed to follow the methodology of Gilbert Walker (1890-1925), unquestionably the greatest of seasonal forecasters when consideration is given to what observational tools (only surface pressure) he had available. Normand (1953) discussed Walker's seasonal prediction philosophy as follows:
>
> 'When Walker started work (on predicting Indian monsoon rainfall) he realized at once that there was little scientific basis for the production of seasonal forecasts. His whole previous scientific career had been devoted to problems in which results could be produced by mathematical analysis from an assured basis of simple principles. It is a sign of the high quality and flexibility of his mind that he could realize that all the skill he had acquired in the past would be of little use to him in his new situation (Director, India Meteorological Service). He decided that since he saw no prospect of treating the weather as a subject to which mathematical reasoning from well established premises could be applied, he would collect all the relevant information which had been recorded and treat it statistically without attempting to trace physical connections between cause and effect'.
>
> 'Walker frankly followed empirical methods, arguing that if, as seems to be the case, physically real relationships can be found by strict statistical methods,

ignorance of their explanation should not stop him from using them, and that the more relationships found empirically the more insight one shall have into the physical relationships of the problem, and the more likely are we to find some ground on which to base a theory'.

"Most of the hindcast skill of these nine monthly forecast parameters (NS, NSD, H, HD, IH, IHD, NTC, TOH, TONS) is obtained from the combination of just three predictors that are not correlated strongly with each other. The forecast skill (or variance explained) of each predictor is largely independent of each other. Most of the forecast skill is obtained by the addition of just three of these individual predictors. For example, the best three predictors for HD are 1, 4, 8. The individual variation of HD which are explained by each of these three variables is 0.24, 0.18 and 0.16. The addition of these three give a variance explained of 0.58. When all three variables are regressed together the variance explained is 0.52, very little less than that obtained by just adding the three individual predictor skill. It is surprising that nearly all of the hindcast skill in all parameter predictions comes from the sum of the three most skillful individual predictors. This is illustrated in Table 7.1."

7.1 Future Work

As noted before, the Gray research group is also working to develop a monthly forecast for September to be issued on 1 August 2002. An October-only forecast may be plausible and further research is being conducted. Factoring the September and October forecasts into our seasonal forecast will likely also add further improvement. The basic differences that we have observed between the character of August versus September TC activity are particularly intriguing and suggest that the predictors associated with each month differ significantly.

It is likely that as a future refinement, some of the August-only predictors will be replaced and/or simply eliminated. Notable in this context is the Galapagos u-parameter

Table 7.1: Hindcast skill of the three most useful predictors in comparison to the skill of the full 4-5 predictor equations.

August Parameter	Predictor Number Individual Variance of 3 Most Skillful Hindcast Predictors	Sum of Best 3 Individual Variation Value	3-parameter Regression	Final 4-5 Parameter Predictor
NS	7(.28), 11(.15), 8(.12)	.55	.46	.55
NSD	1(.33), 3(.19), 11(.19)	.71	.64	.71
H	2(.25), 7(.18), 3(.16)	.69	.53	.57
HD	8(.21), 3(.20), 1(.19)	.60	.57	.69
IH	1(.24), 8(.23), 12(.22)	.69	.54	.68
IHD	9(.26), 1(.23), 4(.20)	.69	.68	.78
NTC	1(.30), 9(.22), 12(.21)	.73	.65	.74
TONS	7(.34), 11(.28), 8(.17)	.79	.65	.68
TOH	7(.25), 8(.19), 11(.18)	.62	.59	.64
Ave.	(.27), (.21), (.18)	.67	.59	.67

which is somewhat redundant and likely can be combined with the v-parameter. Similarly, the very remote and likely ENSO-linked Coral Sea winds probably may be dismissed with little change in skill. These ideas are currently being explored in further studies.

We reiterate that viable physical mechanisms linking some of the predictors to subsequent TC activity are not immediately obvious. For example, it is difficult to infer how parameters such as the January pressure in the southwest U.S. are related to TC activity eight months later. Note that this particular association was observed in 40 years of data and verified in 10 years of independent data. The index does correlate very highly with August SLP in the Atlantic, and this is the likely reason why the predictor is effective. However, it remains unclear why these two areas are connected at such a large lag in time and space. This and many other questions require further study.

Another difficult aspect of the forecast relates the formation of the BI systems at higher latitudes. These cyclones do not form in or from the same environmental conditions/processes as the deep-tropical (TO) activity and do not appear to have any clearly-defined climate signals predicting the likely seasonal incidence of their development. One potential breakthrough would then be an accurate extended range technique for forecasting the development of BI systems as they typically encompass about 20 percent of each season's NTC activity but can account for up to 80 percent of seasonal activity (e.g., 1991). An accurate prediction of BI hurricanes would also lead to the compilation of useful early season (June-July) and late season (November) forecasts.

Possible future comparison work might involve the NCEP/NCAR reanalysis and the ECMWF reanalysis products. It would be useful to determine if the August forecast is as effective when utilizing the somewhat different ECMWF data base for predictor hindcast values. Additionally, if the ECMWF results were closely similar, it would be additional evidence of real relationships between the predictors and August TC activity.

It is hoped that the research and resulting August-only forecast will prove to be as useful as the seasonal TC prediction are for the public. Awareness of the threat that TCs poise to the U.S. will increase by including the August-only forecast with the seasonal prognostication. The associated landfall probabilities should give the public a better, more reasonable idea of the variable likelihood for a hurricane to make landfall along the US coastline and thus provide guidance on possible long-term emergency management decisions. It is planned that this August forecast will be issued by the Colorado State University research team as long as the seasonal forecast is issued.

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