Revised Prediction of Seasonal Atlantic Basin Tropical Cyclone Activity from 1 August

PHILIP J. KLOTZBACH

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

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ABSTRACT

Predictions of the remainder of the season's Atlantic basin tropical cyclone activity from 1 August have been issued by Gray and his colleagues at the Tropical Meteorology Project at Colorado State University since 1984. The original 1 August prediction scheme utilized several predictors, including measures of the stratospheric quasi-biennial oscillation (QBO), West African rainfall, El Niño–Southern Oscillation, and the sea level pressure anomaly and upper-tropospheric zonal wind anomalies in the Caribbean basin. The recent failure of the West African rainfall and QBO relationships with Atlantic hurricanes has led to a general degradation of the original 1 August forecast scheme in recent years. It was decided to revise the scheme using only surface data. The development of the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis has provided a vast wealth of globally gridded meteorological and oceanic data from 1948 to the present. In addition, other datasets have been extended back even further (to 1900), which allows for a large independent dataset. These longer-period datasets allow for an extended period of testing of the new statistical forecast scheme. A new prediction scheme has been developed on data from 1949 to 1989 and then tested on two independent datasets. One of these datasets is the 16-yr period from 1990 to 2005, and the other dataset is from 1900 to 1948. This allows for an investigation of the statistical significance over various time periods. The statistical scheme shows remarkable stability over an entire century. The combination of these four predictors explains between 45% and 60% of the variance in net tropical cyclone activity over the following separate time periods: 1900–48, 1949–89, 1949–2005, and 1900–2005. The forecast scheme also shows considerable skill as a potential predictor for giving the probabilities of United States landfall. Large differences in U.S. major hurricane landfall are also observed between forecasts that call for active seasons compared with those that call for inactive seasons.

1. Introduction

Seasonal prediction of Atlantic basin (the Atlantic Ocean north of the equator, the Caribbean Sea, and the Gulf of Mexico) hurricane activity has been conducted since 1984 when Gray began issuing forecasts from Colorado State University in early June and early August (Gray 1984). Although the hurricane season officially starts on 1 June, an average season has over 90% of its seasonal tropical cyclone activity and approximately 95% of its major [categories 3–5 on the Saffir–Simpson scale; Simpson (1974)] hurricane activity after 1 August. Therefore, a prediction on 1 August is still of considerable usefulness despite being issued 2 months into the hurricane season.

The earlier prediction schemes for Atlantic basin tropical cyclone activity from early August utilized statistical relationships between El Niño, the quasi-biennial oscillation (QBO), and spring and early summer values of Caribbean Basin sea level pressure (Gray 1984). When eastern and central Pacific Ocean equatorial sea surface temperatures were above normal (i.e., El Niño conditions), Atlantic basin hurricane activity tended to be reduced because of an increase in upper-level westerlies and a concomitant increase in vertical wind shear (Gray 1984). The east phase of the QBO was hypothesized to increase upper tropospheric–lower stratospheric vertical wind shear and increase ventilation at upper levels in tropical cyclones, thereby inhibiting their intensification. Finally, although not completely explained in the original paper, high values of Caribbean sea level pressure imply increased subsi-

Corresponding author address: Philip J. Klotzbach, Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.
E-mail: philk@atmos.colostate.edu

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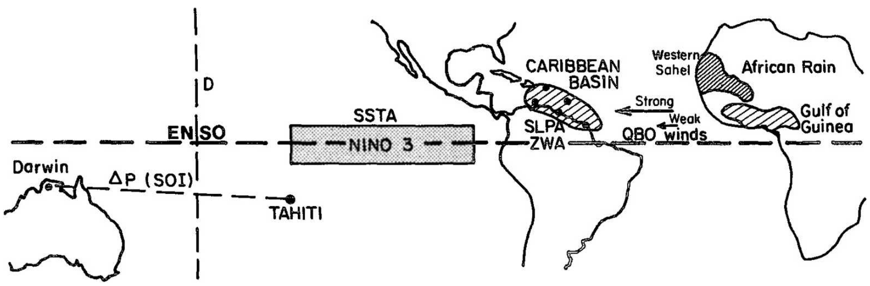

FIG. 1. Locations of areas from which meteorological parameters used in the earlier 1 Aug Atlantic basin seasonal forecast were derived. Reproduced from Gray et al. (1993).

dence, drier air, and likely stronger trade winds (Knaff 1997). All three of these factors inhibit tropical cyclone development. A more in-depth discussion of early Atlantic basin tropical cyclone forecasts is given in Hess and Elsner (1994).

Additional predictors were added to the early August forecast scheme during the first part of the 1990s. These predictors included measures of West African rainfall and upper-tropospheric zonal wind anomalies in the Caribbean (Gray et al. 1993). Drought in the Sahel during the early part of the hurricane season (June–July) was hypothesized to indicate weaker African easterly waves and increased dry air and vertical wind shear in the tropical Atlantic (Landsea and Gray 1992). Positive upper-tropospheric zonal wind anomalies (e.g., stronger westerlies) imply increased vertical wind shear and a southward-shifted intertropical convergence zone, causing anomalous low-level divergence and upper-level convergence in the tropical Atlantic. Both of these conditions are unfavorable for an active hurricane season (Goldenberg and Shapiro 1996; Knaff et al. 2004). Figure 1 shows the locations of the predictors utilized in the early 1990s version of the 1 August forecast scheme.

The Atlantic basin seasonal hurricane forecast from 1 August showed considerable hindcast skill over the period 1950–90, explaining over 60% of the variance in major hurricane activity (Gray et al. 1993). However, this scheme has not worked as well in real-time forecasting since the mid-1990s when the Atlantic returned to very active hurricane conditions associated with the onset of a positive phase of the Atlantic multidecadal oscillation (AMO; Goldenberg et al. 2001).

The primary reason for the failure of the statistical scheme in recent years is a result of the failure of the African rainfall predictors, as well as a noticeable weakening of the relationship between Atlantic hurricanes and the QBO. It is difficult to say why the African rainfall predictors have failed. It could be because of a breakdown in the linkage between African rainfall and Atlantic hurricane activity, or it could be an artifact of changing station measurement quality in West Africa. In addition, Bell and Chelliah (2006) have noted that upper-level divergence over West Africa varies on multidecadal time scales. Therefore, it could be possible that this is more of a multidecadal than year-to-year relationship. Research is ongoing as to why the QBO–Atlantic hurricane relationship has weakened in recent years. Recently, an unpublished manuscript has noted the strong degradation of the QBO–Atlantic hurricane relationship in recent years (C. Landsea 2007, personal communication).

Another reason for redoing the early August statistical forecast is to develop a simple, more concise scheme. The original statistical scheme expanded over time, to include consideration of 16 predictors by August 2001. Mostly different predictors were utilized to predict each tropical cyclone metric (i.e., named storms, hurricanes, etc.). Because the pool of predictors was so large, it often led to somewhat divergent statistical forecasts for individual tropical cyclone parameters. Therefore, these statistical forecasts lacked internal consistency. For example, in August 2001, 6.7 named storms were predicted (about 75% of the post–1 August climatological average), whereas 5.5 major hurricane days were predicted (about 110% of the post–1 August climatological average) (Gray et al. 2001). For reference, a total of 15 named storms and 4.25 major hurricane days occurred during 2001; so clearly, for this particular forecast, the statistical prediction of major hurricane days was much closer to the mark than was the named storm prediction.

Several new datasets have recently been developed that provide data on a global grid for a variety of meteorological and oceanic parameters including zonal wind, sea level pressure, sea surface temperature, etc. Some of these datasets, especially those that evaluate surface parameters, extend back to 1900 or even as far back as the mid–nineteenth century. It was decided to develop a new 1 August seasonal forecast scheme that utilizes these new datasets as well as some recent physical insights into other potential modulators of Atlantic hurricane activity. Section 2 discusses the data used in this new 1 August forecast, and section 3 examines the considerable multidecadal variability that is evident in Atlantic basin tropical cyclone activity. Section 4 explains the methodology used to develop the new forecast. Section 5 discusses the results of the forecast development, and section 6 examines the likely physical relationships between the predictors and Atlantic basin hurricane activity. Section 7 discusses the potential use of the scheme for issuing U.S. tropical cyclone landfall probabilities, and conclusions are presented in section 8.

2. Data

Atlantic basin hurricane activity from 1900 to 2005 was calculated from the National Hurricane Center's "best track" data files (Jarvinen et al. 1984). This dataset provides the best estimate of a storm's intensity in 5-kt increments for every 6-h period of the storm's existence. Recent changes made by the Atlantic Hurricane Database Reanalysis Project for tropical cyclones that occurred during the early part of the twentieth century (1900–14) (Landsea et al. 2004) have been included in this analysis.

The primary data source used for selecting predictors was the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis from 1949 to 2005 (Kalnay et al. 1996; Kistler et al. 2001). The reanalysis provides global data on a 2.5° × 2.5° grid for a large number of atmospheric and oceanic parameters including sea surface temperature, sea level pressure, zonal wind, meridional wind, etc. The model used to generate the reanalysis product was frozen at the beginning of the reanalysis, and, therefore, there should not be any spurious jumps or discontinuities in the data due to model changes. It should also be noted that all data used as predictors selected were from the reanalysis "A" variables (Kalnay et al. 1996). These variables have more consistency checks (e.g., wind–pressure relationships, thermal wind balance, etc.) and are more constrained by observations than are some other variables (e.g., velocity potential, outgoing longwave radiation, etc.).

One of the predictors selected for forecasting Atlantic basin hurricane activity was the Niño-3 index located in the tropical eastern Pacific. This index is a measure of sea surface temperatures from 5°S to 5°N and 150° to 90°W. The Climate Prediction Center's analysis of the Niño-3 index is utilized in this paper for the 1950–2005 period. Values were obtained from the Climate Prediction Center's Web site (http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices). The Niño-3 index from 1900 to 1949 was derived from the Hadley Centre's Sea Ice and Sea Surface Temperature dataset (Rayner et al. 2003) using calculations available from the Climate Diagnostics Center's time series Web page (http://www.cdc.noaa.gov/Pressure/Timeseries/).

Two additional datasets were utilized for the earlier independent dataset from 1900 to 1948. Sea level pressure values were calculated from the Hadley Center SLP dataset (Basnett and Parker 1997). Earlier-period sea surface temperatures were calculated from the Kaplan SST dataset (Kaplan et al. 1998).

3. Atlantic basin multidecadal variability

The Atlantic basin has more year-to-year and multidecadal variability than does any other tropical cyclone basin. There are distinct periods in the historical hurricane record, of approximately 25–40 yr in length, when Atlantic major (categories 3–5) hurricane activity was much more frequent than in other periods of a similar length. For example, many more major hurricanes were observed in the Atlantic from 1926 to 1969 and 1995 to the present than were observed from 1900 to 1925 and from 1970 to 1994. This variability has been discussed at length in several recent papers and has been termed the AMO (Goldenberg et al. 2001). In general, when the AMO is positive, North Atlantic and tropical Atlantic sea surface temperatures are warmer, vertical wind shear is reduced, and consequently more active tropical cyclone seasons occur (Bell and Chelliah 2006).

Atlantic basin multidecadal variability is greatest for major hurricanes, which, although accounting for only approximately 25% of all Atlantic basin tropical cyclones, do approximately 80%–85% of the total damage when normalized by population, inflation, and wealth per capita (Pielke and Landsea 1998). Table 1 displays the average number of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days, and net tropical cyclone (NTC) activity for the multidecadal periods of 1900–25, 1926–69, 1970–94, and 1995–2005. See section 4 for a more in-depth discussion of NTC activity. The earlier periods were likely underestimated somewhat because of a lack of satellite imagery and aircraft reconnaissance. More than twice as many major hurricanes and major hurricane days occurred during the 1926–69 and 1995–2005 periods, when the AMO was in its positive phase, compared with 1900–25 and 1970–94, when the AMO was in its negative phase.

TABLE 1. Average number of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days, and NTC activity per year for the multidecadal periods of 1900–25, 1926–69, 1970–94, and 1995–2005.

Period	Named storms	Named storm days	Hurricanes	Hurricane days	Major hurricanes	Major hurricane days	NTC activity
1900–25	6.4	38.9	3.6	15.4	1.2	3.2	64.7
1926–69	9.4	52.2	5.6	24.8	2.6	6.5	107.5
1970–94	8.6	38.7	5.0	16.0	1.5	2.5	72.4
1995–2005	14.8	79.8	8.5	36.6	4.1	10.9	167.5

It has been hypothesized that the AMO is driven by variations in the strength of the Atlantic thermohaline circulation (Gray et al. 1997; Goldenberg et al. 2001). Direct measurements of the strength of the overturning circulation are unavailable, so a proxy measure of AMO strength has been created using annually averaged North Atlantic basin sea surface temperatures from 50° to 60°N and 10° to 50°W and annually averaged North Atlantic sea level pressures from 0° to 50°N and 10° to 70°W. Sea surface temperature values were calculated from the Kaplan SST dataset (Kaplan et al. 1998), while sea level pressure values were calculated from the Hadley SLP dataset (Basnett and Parker 1997). When sea surface temperatures are above normal and sea level pressure values are below normal, the AMO is judged to be in its positive phase. Standardized values of sea level pressure (SLP) and SST for the North Atlantic region over the periods of 1900–25, 1926–69, 1970–94, and 1995–2005 are shown in Table 2. Anomalies are calculated from the 1900–99 base period. Note the large variations in SLP and SST over these periods. There are clearly large-scale variations in atmospheric and oceanic parameters between active and inactive phases of the AMO.

4. Methodology

One of the likely reasons why earlier statistical forecasts of Atlantic basin hurricane activity have had a significant reduction in forecast skill when applied to independent data was the general lack of data for independent tests. This was largely because of the unavailability of earlier-period datasets (e.g., 1900–50) in the 1980s and 1990s. With the recent development of new surface datasets for the first half of the twentieth century, it is believed that more robust forecast schemes can be formulated, because they can be developed on 40+ yr of data and then tested on an additional 40+ yr of data. If a scheme shows skill in both long-term periods, it is much less likely to fail when applied on new independent datasets.

TABLE 2. Annually averaged values of North Atlantic basin SST and SLP for the multidecadal periods of 1900–25, 1926–69, 1970–94, and 1995–2005.

Period	North Atlantic SST (50°–60°N, 10°–50°W)	North Atlantic SLP (0°–50°N, 10°–70°W)
1900–25	−0.5	0.2
1926–69	0.7	−0.4
1970–94	−0.8	0.6
1995–2005	0.8	−0.2

Earlier seasonal and monthly prediction schemes for predicting Atlantic basin hurricane activity have attempted to predict the activity of a variety of seasonal indices including named storms, named storm days, hurricanes, hurricane days, etc. (e.g., Klotzbach and Gray 2003, 2004; Gray et al. 1992, 1993, 1994; Blake and Gray 2004). This technique often led to a selection of a large number of predictors, which likely overfit the forecast scheme.

In this new scheme, I attempt to find predictors that explain the variance in both dependent and independent datasets for the NTC activity metric (Klotzbach and Gray 2004). NTC is an aggregate measure of the following six parameters normalized by their climatological averages: named storms, named storm days, hurricanes, hurricane days, major hurricanes, and major hurricane days. By definition, an NTC value of 100 indicates an average season. Values over 100 indicate above-average seasonal activity, and values below 100 indicate below-average seasonal activity. For reference, the largest NTC value observed since 1900 is 2005, which recorded an NTC of 277, and the smallest NTC value observed since 1900 is 1914 which accrued an NTC of 3.

Following the prediction of NTC, all other Atlantic seasonal predictands (e.g., named storms, named storm days, hurricanes, hurricane days, etc.) are then adjusted from their climatological average values by the NTC prediction divided by 100. For example, an average Atlantic basin hurricane season has approximately 10 named storms. If an NTC of 120 is predicted, the total number of named storms predicted would be (10×1.20) = 12. This methodology helps keep the statistical scheme much simpler by using many fewer predictors than if each predictand were hindcast individually.

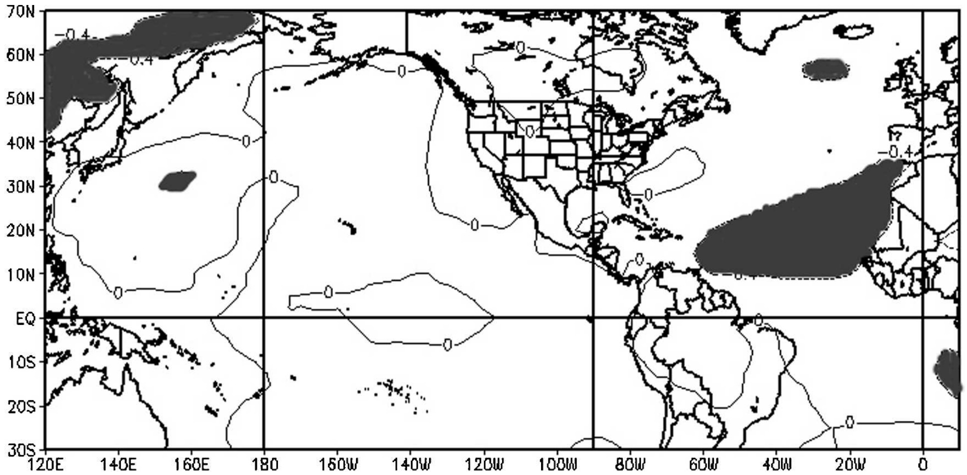

Fig. 2. Linear correlation map between June–July sea level pressure and post–1 Aug NTC from 1949 to 1989. Areas shaded in gray correlated at ($r > |0.4|$), which is approximately the 99% confidence level of statistical significance for a two-tailed Student's t test. Note the large shaded area in the subtropical Atlantic.

Predictors were selected from the NCEP–NCAR reanalysis using the Climate Diagnostic Center's "Linear Correlations" Web page (http://www.cdc.noaa.gov/Correlation), which allows for correlating various atmospheric and oceanic fields with a particular index. In this case, sea level pressure and sea surface temperature fields were correlated with NTC activity for 1949–89. The 1990–2005 period was set aside as an independent dataset, and the predictors selected were also tested over an earlier 49-yr period (1900–48). The earlier-period (1900–48) correlation tests were done utilizing the Hadley SLP and Kaplan SST datasets discussed previously. Figure 2 shows an example of the linear correlation map between June–July sea level pressure and post–1 August NTC activity from 1949 to 1989.

Predictors were added using a stepwise regression technique (Wilks 1995), and they were only kept in the forecast scheme if they explained an additional 2% of the variance in the dependent data (1949–89), the recent independent dataset (1990–2005), and the older independent dataset (1900–48). It is believed that if a predictor added additional variance in all three datasets, it is likely robust and is explaining additional variance not explained by the other predictors.

5. Results

Figure 3 and Table 3 display and describe the predictors selected for the 1 August forecast for the remainder of the hurricane season. Table 4 shows the

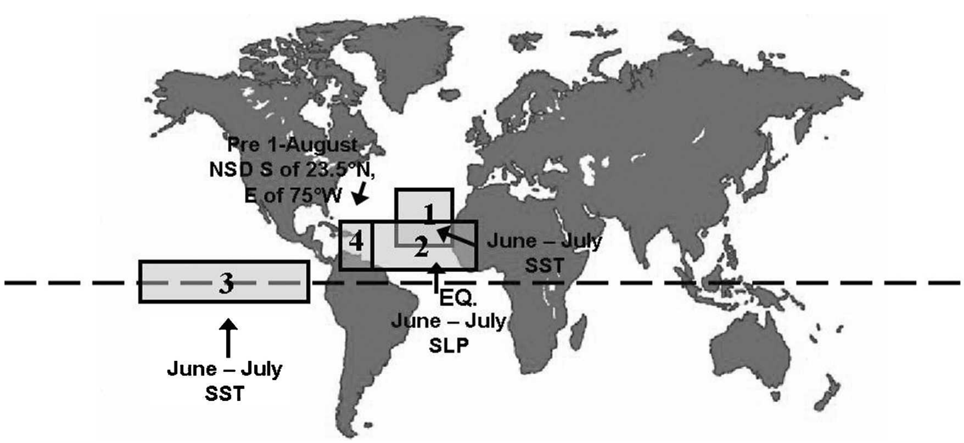

Fig. 3. Map of the predictors utilized in the new 1 Aug forecast scheme for Atlantic basin hurricane activity. See Table 3 for exact locations.

TABLE 3. Locations of predictors utilized in the new 1 Aug forecast for Atlantic basin hurricane activity. The sign of the predictor associated with increased Atlantic basin tropical cyclone activity is in parentheses.

Predictor No.	Predictor name	Location
1	Jun–Jul SST in the subtropical Atlantic (+)	20°–40°N, 35°–15°W
2	Jun–Jul SLP in the tropical and subtropical Atlantic (−)	10°–20°N, 60°–10°W
3	Jun–Jul Niño-3 SST index (−)	5°S–5°N, 150°–90°W
4	Before 1 Aug tropical Atlantic named storm days (+)	South of 23.5°N, east of 75°W

increase in variance explained for NTC using the stepwise regression technique for each time period (1949–89, 1990–2005, 1900–48, 1949–2005, and 1900–2005). The increases in variance explained for the time periods of 1990–2005, 1900–48, 1949–2005, and 1900–2005 were calculated using the equations developed on 1949–89. The variance explained is even higher in the 1990–2005 independent dataset than over the 1949–89 developmental dataset. This is a testament to the remarkable stability of the scheme. It should also be noted that this independent dataset is only 16 yr in length. Often, large correlations can be obtained when evaluating a scheme over a short time period. If the scheme were to fail in one or two years, the variance explained would fall to values more similar to what were observed during the 1949–89 period.

Note that the addition of each predictor to the forecast scheme adds at least 2% in additional variance explained for each time period. The equations for 1949–89 were derived from the predictor's standardized anomaly values. This was done because data from 1900 to 1948 use different time series, and, therefore, the means and standard deviations are slightly different.

The forecast scheme showed considerable stability between time periods, and therefore, it was decided that for real-time forecasts of post–1 August NTC in 2006 and in future years, equations from 1949 to 2005 would be used. Table 5 displays the stepwise regression technique for 1949–2005 using equations developed over the full period (e.g., 1949–2005). Also, the skill of the independent dataset from 1900 to 1948 is evaluated using equations developed from 1949 to 2005. Note that the skill over the 1900–48 time period improves slightly using the equations developed over the longer period (e.g., 1949–2005 compared with 1949–89).

When evaluating the hindcast skill of the equations developed over the 1949–2005 period, it is encouraging to note that the variance explained over the independent dataset from 1900 to 1948 shows similar levels of variance explained [47% (1900–48) compared with 52% (1949–2005) in the dependent dataset]. This level of forecast degradation is slightly less than what would be expected from jackknife or cross-validation regression techniques (Elsner and Schmertmann 1994). In a cross-validation exercise, the year that is being hindcast is omitted from the development dataset. This exercise is generally considered to provide an upper bound on likely real-time forecast skill for the statistical scheme. When cross-validation is applied to the 1949–2005 dependent dataset, the variance explained over the period is 42%, which is smaller than the variance explained in the independent dataset. This adds increased confidence that this forecast scheme is quite stable between time periods and should be reasonably skillful in the future. The prediction scheme shows remarkable skill over the entire time period (1900–2005), explaining 63% of the variance in NTC activity over the past 106 yr.

Table 6 displays hindcasts of post–1 August NTC by year from 1949 to 2005, using equations developed on the full 1949–2005 period. The hindcast scheme improves upon a climatological forecast by 35% for average error, 52% for mean square error, and 31% for root-mean-square error. It should be noted that the hindcasts tend to underestimate NTC during warm AMO periods while hindcasts tend to overestimate NTC during cool AMO periods. This is to be expected,

TABLE 4. Stepwise regression technique showing the improvement in variance explained for NTC with the addition of predictors to the August forecast scheme for seasonal Atlantic basin hurricane activity from 1949–89, 1990–2005, 1900–48, and 1900–2005, respectively. The variance explained values are calculated based on equations developed over 1949–89. Predictor numbers are the same as in Table 3.

Predictor No.	1949–89 (r^2) (41 yr)	1990–2005 (r^2) (16 yr)	1900–48 (r^2) (49 yr)	1949–2005 (r^2) (57 yr)	1900–2005 (r^2) (106 yr)
1	0.16	0.41	0.23	0.25	0.32
1, 2	0.39	0.56	0.32	0.37	0.45
1, 2, 3	0.43	0.67	0.38	0.41	0.51
1, 2, 3, 4	0.45	0.71	0.45	0.49	0.60

TABLE 5. Stepwise regression technique showing the improvement in variance explained for NTC with the addition of predictors to the August forecast scheme for seasonal Atlantic basin hurricane activity from 1949–2005, 1900–48, and 1900–2005. The variance explained values are calculated based on equations developed over 1949–2005. Predictor numbers are the same as in Table 3.

Predictor No.	1949–2005 (r^2) (57 yr)	1900–48 (r^2) (49 yr)	1900–2005 (r^2) (106 yr)
1	0.25	0.23	0.32
1, 2	0.38	0.34	0.47
1, 2, 3	0.43	0.39	0.53
1, 2, 3, 4	0.52	0.47	0.63

because statistical techniques based on linear regression analysis are conservative by their definition. Figure 4 displays a time series of post–1 August NTC hindcasts compared with observed post–1 August NTC from 1949 to 2005. Note that the hindcasts generally follow the observations quite closely, as evidenced by the 52% variance explained over the 1949–2005 time period.

Table 7 displays the individual correlations between each predictor and post–1 August NTC for the dependent dataset of 1949–2005 and the independent dataset of 1900–48. The statistical significance of each predictor is tested using a two-tailed Student's t test. Although several of these predictors had already been known to be related to upcoming hurricane activity, it was decided to use a two-tailed Student's t test in order to be conservative with statistical significance estimates.

For the 1949–2005 time period, a correlation of 0.26 is required for 95% significance and a correlation of 0.34 is required for 99% significance. For the 1900–48 time period, a correlation of 0.28 is required for 95% significance and a correlation of 0.37 is required for 99% significance. All correlations are significant at the 95% level except for the Niño-3 index from 1900 to 1948. However, this correlation is just slightly below the 95% level, and it has been well documented that ENSO effects Atlantic hurricane activity (Gray 1984; Goldenberg and Shapiro 1996; Klotzbach and Gray 2004). In addition, the quality of sea surface temperature data prior to 1949 is somewhat suspect, especially in data-void regions such as Niño-3. In earlier-period SST datasets such as the Hadley SST dataset during the period 1900–48, EOF analysis was used to spatially smooth data, and therefore, some of the predictive signal may have been lost in the smoothing. The stability of the correlations in both dependent and independent datasets gives us increased confidence in the use of these predictors in the forecast scheme.

Table 8 displays the intercorrelations between the four predictors over the dependent dataset from 1949 to 2005, while Table 9 displays these intercorrelations over the independent dataset from 1900 to 1948. All correlations are below $r = |0.4|$ ($r^2 < 0.16$). There is a marginally significant (90% level) negative correlation between the subtropical Atlantic SST and the tropical Atlantic SLP predictor over both time periods (1949–2005 and 1900–48). This is to be expected, as higher sea level pressure values indicate stronger trade winds, driving more upwelling and cooling sea surface temperatures. However, the location of these two predictors is such that they are only weakly positively correlated, and there is considerable additional information added by considering both predictors. The correlations tend to be fairly stable between the two time periods. Having predictors that are mostly independent of each other is important, because this implies that new independent information is being added to the scheme with the addition of another predictor. The independence of these predictors is not surprising, as it has already been noted that each predictor added at least an additional 2% of the variance to the forecast scheme.

As was briefly mentioned earlier, the forecast scheme works quite well on independent data. Using the exact same equations as were used from 1949 to 2005, 47% of the variance is explained over the 1900–48 time period. It is interesting to note that NTC values are overforecast considerably during the first part of the twentieth century. The mean for observed NTC from 1900 to 1948 is 68, while the mean for predicted NTC from 1900 to 1948 is 97 based on equations developed on 1949–2005 data. This is likely because the observational network during the first part of the twentieth century missed several tropical cyclones each year, especially systems that formed and dissipated over the open Atlantic. Therefore, observed NTC values during the first part of the twentieth century are most likely underestimated somewhat.

Equations for the 1900–48 time period using data for that same time period are then developed. In a sense, this is making the earlier period also a hindcast dataset. The variance explained only increases slightly when this is done (improves r^2 from 47% to 51%), but it removes any NTC over- or underestimate, because the equations are now trained to the earlier-period dataset. Figure 5 displays a time series of post–1 August NTC hindcasts compared with observed post–1 August NTC from 1900 to 1948 using these new equations.

The stability of the forecast scheme and the stability of the individual correlations between predictors and post–1 August NTC gives increased confidence that this forecast scheme will likely have long-term stability. The

TABLE 6. Observed post–1 Aug NTC, hindcast post–1 Aug NTC, hindcast error, and error using a climatological forecast of post–1 Aug NTC of 92. Hindcast values are derived from equations based on the 1949–2005 period.

Year	Obs post–1 Aug NTC	Hindcast post–1 Aug NTC	Hindcast error	Error using climatology
1949	117	131	−14	25
1950	230	120	110	138
1951	95	131	36	−3
1952	91	138	−47	−1
1953	110	114	−4	18
1954	116	110	6	24
1955	187	167	20	95
1956	58	84	−26	−34
1957	63	90	−27	−29
1958	131	104	27	39
1959	72	100	−28	−20
1960	79	160	−81	−13
1961	190	149	41	98
1962	32	111	−79	−60
1963	111	96	15	19
1964	155	126	29	63
1965	79	55	24	−13
1966	91	153	−62	−1
1967	93	95	−2	1
1968	23	78	−55	−69
1969	146	114	32	54
1970	54	86	−32	−38
1971	89	59	30	−3
1972	19	22	−3	−73
1973	42	99	−57	−50
1974	72	69	3	−20
1975	79	109	−30	−13
1976	79	63	16	−13
1977	45	86	−41	−47
1978	81	74	7	−11
1979	81	87	−6	−11
1980	129	100	29	37
1981	105	101	4	13
1982	30	30	0	−62
1983	31	36	−5	−61
1984	74	75	−1	−18
1985	97	95	2	5
1986	28	43	−15	−64
1987	46	80	−34	−46
1988	118	132	−14	26
1989	123	149	−26	31
1990	88	127	−39	−4
1991	54	71	−17	−38
1992	64	51	13	−28
1993	50	42	8	−42
1994	32	50	−18	−60
1995	205	191	14	113
1996	163	130	33	71
1997	33	39	−6	−59
1998	163	140	23	71
1999	182	120	62	90
2000	134	92	42	42
2001	127	111	16	35
2002	78	38	40	−14
2003	153	133	20	61
2004	228	116	112	136
2005	198	173	25	106

Table 6. *Continued*

Year	Obs post–1 Aug NTC	Hindcast post–1 Aug NTC	Hindcast error	Error using climatology
Avg error			|28|	|43|
% improvement			35%	
Mean square error			1399	2937
% improvement			52%	
RMSE			37	54
% improvement			31%	

next section discusses the likely physical relationships between individual predictors and Atlantic basin hurricane activity.

6. Physical relationships between predictors and Atlantic basin hurricane activity

One method to better understand physical relationships between predictors and Atlantic basin hurricane activity is to use the NCEP–NCAR reanalysis correlations Web site (http://www.cdc.noaa.gov/Correlation). For example, using this Web page, a user can correlate a predictor field, for example tropical Atlantic sea surface temperatures in June and July, and see how that field correlates with Atlantic basin NTC. Because these predictors occur just before the start of the busy part of the hurricane season, it is somewhat easier to tie them physically to Atlantic basin hurricanes than some earlier season predictors. I now discuss the hypothesized physical relationships between each individual predictor and post–1 August Atlantic basin hurricane activity.

a. Predictor 1: June–July SST in the northeastern subtropical Atlantic (20°–40°N, 35°–15°W)

Warm sea surface temperatures in this area in June–July correlate very strongly with anomalously warm sea surface temperatures in the tropical Atlantic throughout the upcoming hurricane season. Anomalously warm sea surface temperatures are important for development and intensification of tropical cyclones by infusing more latent heat into the system (Shapiro and Goldenberg 1998). Warmer SSTs reduce static stability, which weakens the subsidence associated with the subtropical high and consequently reduces the trade winds during the remainder of the season (e.g., Namias 1973). Weaker trade winds cause less evaporation and upwelling of the sea surface, which therefore feeds back into keeping the tropical Atlantic warm. In addition, weaker trade winds imply that there is less vertical wind shear across the tropical Atlantic. Weak wind shear is favorable for tropical cyclone development and intensification (Gray 1968, 1984; Goldenberg and Shapiro 1996; Knaff et al. 2004). Finally, there is a strong positive correlation (~0.5) between anomalously warm June–July SSTs in the subtropical northeastern Atlantic and low sea level pressures in the tropical Atlantic and Caribbean Basin during the heart of the hurricane season (August–October). Low sea level pressures imply decreased subsidence and enhanced midlevel moisture. Both of these conditions are favorable for tropical cyclogenesis and intensification (Knaff 1997).

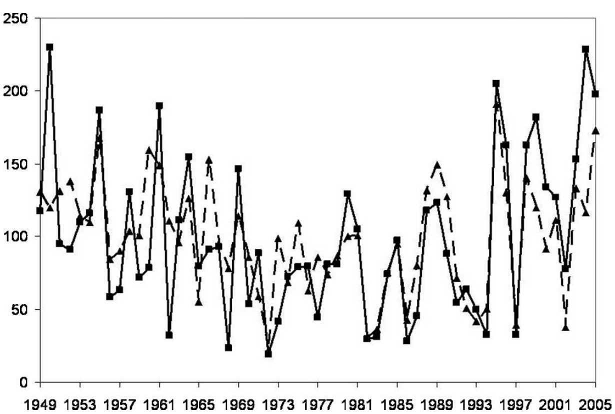

Fig. 4. Observed post–1 Aug NTC (solid line) vs hindcast post–1 Aug NTC (dashed line) for 1949–2005. Nonjackknifed variance (r^2) explained is 0.52.

b. Predictor 2: June–July SLP in the tropical Atlantic (10°–25°N, 60°–10°W)

Low sea level pressure in the tropical Atlantic in June–July implies that early summer conditions in the tropical Atlantic are favorable for an active tropical

Table 7. Correlations between individual predictors and post–1 Aug NTC for 1900–48 and 1949–2005. Correlations significant at the 95% level for a two-tailed Student's *t* test are italicized while correlations significant at the 99% level are set in boldface. Predictor numbers are the same as in Table 3.

Predictor No.	1900–48 (*r*)	1949–2005 (*r*)
1	**0.48**	**0.50**
2	**−0.46**	**−0.49**
3	−0.25	*−0.33*
4	**0.56**	**0.39**

TABLE 8. Intercorrelations between predictors over the dependent dataset from 1949 to 2005. Predictor numbers are the same as in Table 3.

Predictor No.	1	2	3	4
1	—	−0.28	0.02	0.14
2	−0.28	—	0.36	−0.17
3	0.02	0.36	—	0.01
4	0.14	−0.17	0.01	—

cyclone season with increased vertical motion, decreased stability, and enhanced midlevel moisture. There is a strong autocorrelation ($r > 0.5$) between June–July sea level pressure anomalies and August–October sea level pressure anomalies in the tropical Atlantic. Low sea level pressure in the tropical Atlantic also correlates quite strongly ($r > 0.5$) with reduced trade winds (weaker easterlies) and anomalously easterly upper-level winds (weaker westerlies). The combination of these two features implies weaker vertical wind shear and therefore more favorable conditions for tropical cyclone development in the Atlantic (Gray 1968, 1984; Goldenberg and Shapiro 1996). In addition, lower-than-normal sea level pressure usually indicates more midlevel moisture, which is an important ingredient for tropical cyclone genesis and intensification (Gray 1968).

c. *Predictor 3: June–July Niño-3 index (5°S–5°N, 150°–90°W)*

Cool sea surface temperatures in the Niño-3 region during June–July imply that a La Niña event is currently present. In general, positive or negative anomalies in the Niño-3 region during the early summer persist throughout the remainder of the summer and fall. El Niño conditions shift the center of the Walker circulation eastward, which causes increased convection over the central and eastern tropical Pacific. This increased convection in the central and eastern Pacific manifests itself in anomalous upper-level westerlies across the Caribbean and tropical Atlantic, thereby increasing vertical wind shear and reducing Atlantic basin

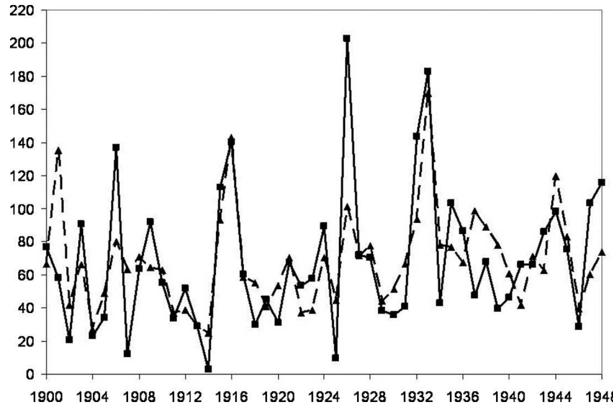

FIG. 5. Observed post–1 Aug NTC (solid line) vs hindcast post–1 August NTC (dashed line) for 1900–48. Nonjackknifed variance (r^2) explained is 0.51.

hurricane activity. The relationship between ENSO and Atlantic hurricane activity has been well documented in the literature (e.g., Gray 1984; Goldenberg and Shapiro 1996; Elsner 2003; Bell and Chelliah 2006).

d. *Predictor 4: Named storm days south of 23.5°N, east of 75°W*

Most years do not have named storm formations in June and July in the tropical Atlantic; however, if tropical Atlantic formations do occur, it indicates that an active hurricane season is likely. For example, the 6 yr with the most named storm days in the deep Tropics in June and July (since 1949) are 1966, 1969, 1995, 1996, 1998, and 2005. All six of these seasons were very active. When storms form in the deep Tropics in the early part of the hurricane season, it indicates that conditions are already very favorable for TC development. In general, the start of the hurricane season is restricted by thermodynamics (warm SSTs, unstable lapse rates, and midlevel moisture) (DeMaria et al. 2001), and therefore deep tropical activity early in the hurricane season implies that the thermodynamics in the tropical Atlantic are already quite favorable for tropical cyclone (TC) development. Also, this predictor's correlation with seasonal NTC is 0.39 over the 1949–2005 period, and when tested on independent data (1900–48), the correlation actually improves to 0.56, which gives us increased confidence in its use as a seasonal predictor.

TABLE 9. Intercorrelations between predictors over the independent dataset from 1900 to 1948. Predictor numbers are the same as in Table 3.

Predictor No.	1	2	3	4
1	—	−0.32	−0.02	0.32
2	−0.32	—	0.04	−0.36
3	−0.02	0.04	—	−0.21
4	0.32	−0.36	−0.21	—

7. Post–1 August NTC prediction and U.S. landfalling hurricanes

It has been shown in previous forecast papers that there is a strong relationship between hindcast values of

Table 10. Number and ratio of landfalling named storms (NS), hurricanes (H), and major hurricanes (MH) for the United States (US), EC, and GC for the top 5 and bottom 5, the top 10 and bottom 10, and the top 15 and bottom 15 post 1–Aug NTC hindcast years from 1949 to 2005.

Hindcast landfall occurrences	US NS	US H	US MH	EC NS	EC H	EC MH	GC NS	GC H	GC MH
Top 5	18	14	8	11	9	5	7	5	3
Bottom 5	13	3	1	5	0	0	8	3	1
Ratio (%)	138	467	800	220	n/a	n/a	88	167	300
Top 10	35	23	10	18	13	6	17	10	4
Bottom 10	23	9	6	12	4	3	11	5	3
Ratio (%)	152	256	167	150	325	200	155	200	133
Top 15	46	28	12	25	16	8	21	12	4
Bottom 15	33	15	7	18	7	3	15	8	4
Ratio (%)	139	187	171	139	229	267	140	150	100

NTC and U.S. landfalling tropical cyclones (Klotzbach and Gray 2003; Blake and Gray 2004; Klotzbach and Gray 2004). These relationships are usually strongest for major hurricanes, which are the storms that are of greatest importance. Major hurricanes, although accounting for only 20%–25% of all named storms, do approximately 80%–85% of the total economic damage when normalized by population, inflation, and wealth per capita (Pielke and Landsea 1998). The relationship between landfalling tropical cyclones after 1 August and hindcast values of post–1 August NTC is quite significant. For example, using the hindcast equations developed over the 1949–2005 period, in the 10 yr from 1949 to 2005, where the largest values of NTC were hindcast, 23 hurricanes made U.S. landfall after 1 August compared with only 9 hurricanes in the 10 yr with the lowest hindcast NTC values—a ratio of greater than 2.5 to 1. Eight major hurricanes made landfall in the top five hindcasts compared with only one major hurricane in the five lowest hindcasts. Table 10 displays landfalling named storms, hurricanes, and major hurricanes for the U.S. east coast (EC), the Gulf coast (GC) and U.S. coastline for the top 5–bottom 5, top 10–bottom 10, and top 15–bottom 15 NTC hindcast values from 1949 to 2005. For reference, the EC–GC breakdown for landfalling storms is approximately 100 mi north of Tampa, Florida. Storms making landfall in southwest Florida, including the Florida Keys, are counted as EC storms in this analysis. The breakdown of the coastline was done this way, because, in general, storms making landfall along the Florida panhandle and westward tend to have their genesis in the Gulf of Mexico, while storms in southwest Florida and eastward tend to have their genesis in the North Atlantic.

To provide a visualization of some of the significant differences between storms making landfall in high and low NTC hindcast years, Fig. 6 displays EC landfalling hurricanes for the top 10 and bottom 10 NTC hindcast years. Thirteen storms made landfall in the top 10 NTC hindcast years compared with only four storms in the bottom 10 NTC hindcast years.

These ratios become even stronger in the independent dataset from 1900 to 1948 (Table 11). The equa-

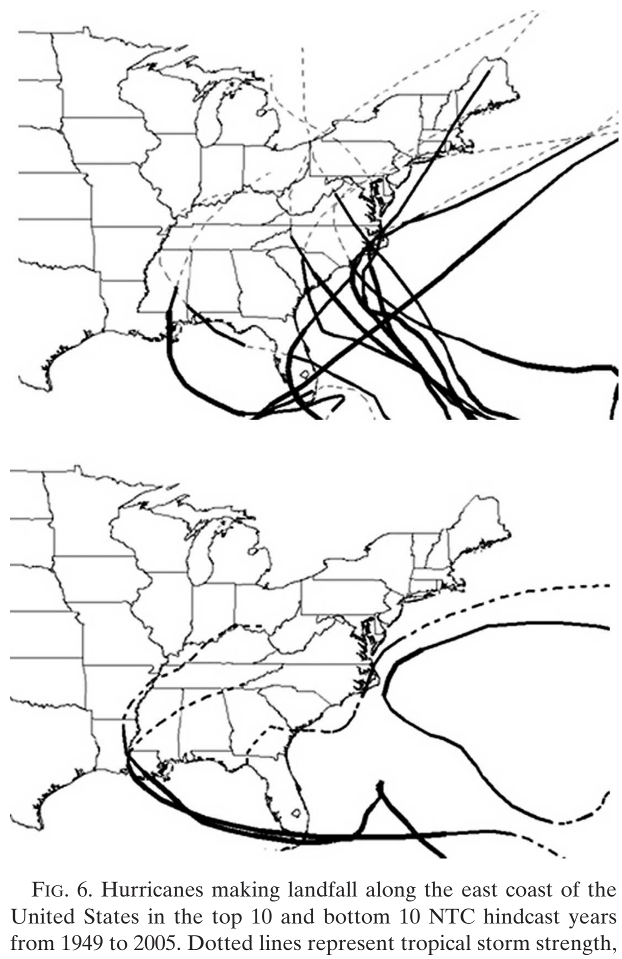

Fig. 6. Hurricanes making landfall along the east coast of the United States in the top 10 and bottom 10 NTC hindcast years from 1949 to 2005. Dotted lines represent tropical storm strength, thin solid lines represent hurricane strength, and thick solid lines represent major hurricane strength.

TABLE 11. Number and ratio of landfalling named storms, hurricanes, and major hurricanes for the US, EC, and GC for the top 5 and bottom 5, the top 10 and bottom 10, and the top 15 and bottom 15 post–1 Aug NTC forecast years from 1900 to 1948.

Forecast landfall occurrences	US NS	US H	US MH	EC NS	EC H	EC MH	GC NS	GC H	GC MH
Top 5	25	13	7	14	8	5	11	5	2
Bottom 5	9	4	2	6	3	1	3	1	1
Ratio (%)	278	325	350	233	267	500	367	500	200
Top 10	45	26	15	20	12	8	25	14	7
Bottom 10	19	10	2	9	5	1	10	5	1
Ratio (%)	237	260	750	222	240	800	250	280	700
Top 15	59	36	19	27	19	11	32	17	8
Bottom 15	32	16	5	15	8	2	17	8	3
Ratio (%)	184	225	380	180	238	550	188	213	267

tions developed on 1949–2005 were used to predict NTC activity from 1900 to 1948, and then seasons from 1900 to 1948 were ranked using these predictions. Twenty-six hurricanes made landfall in the top 10 predicted NTC years compared with only 10 hurricanes in the 10 lowest years. Also, 15 major hurricanes made landfall in the top 10 predicted NTC years compared with only 2 major hurricanes in the 10 lowest years.

It is clear from these significant ratios that the use of NTC predictions certainly has the potential to add skill to landfall probabilities beyond that specified by climatology. These NTC predictions will be integrated into the landfall probability forecasts issued by the Tropical Meteorology Project.

8. Future work and conclusions

A significant amount of skill has been demonstrated using a simple hurricane prediction scheme that uses only four surface predictors to forecast hurricane activity after 1 August. This scheme not only showed skill on a dependent dataset of 1949–89 but also shows nearly equivalent levels of skill during an earlier period from 1900 to 1948 and during a more recent period from 1990 to 2005. Because this scheme shows considerable stability over a 106-yr period, it likely will show similar amounts of skill in the future.

The Tropical Meteorology Project's statistical forecast schemes issued at earlier lead times (i.e., early December, early April, and early June) will be reevaluated in the next couple of years. Because extensive databases have been developed for surface fields, such as sea level pressure and sea surface temperature, back to 1900, the intention is to investigate the possibility of redesigning these earlier-season forecasts as well. Monthly forecasts will also be reanalyzed (individual monthly forecasts for August, September, and October) to see if these can be improved using a similar methodology.

Seasonal hurricane forecasts and landfall probabilities are of considerable use to the insurance industry, emergency managers, and coastal residents alike. With continued research and a greater wealth of datasets, improved seasonal forecasts with increasing levels of skill can likely be developed.

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