Improving Seasonal Hurricane Predictions for the Atlantic Basin

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ABSTRACT

This paper demonstrates that improved forecasts of the annual number of hurricanes in the Atlantic tropical basin are possible by separating tropical-only hurricanes from hurricanes influenced by extratropical factors. It is revealed that variables previously shown to have a predictive relationship with the annual number of Atlantic hurricanes have a significantly stronger predictive association with the number of hurricanes formed solely from tropical mechanisms. This stronger relationship exists for extended-range (6-month lead) as well as for short-range (0-month lead) forecast models. Any future study of seasonal hurricane activity over this region should consider tropical-only hurricanes as separate from hurricanes influenced by baroclinic disturbances. The annual number of hurricanes that form or intensify as a result of interactions with baroclinic disturbances appears unrelated to significant tropical or midlatitude atmospheric anomalies and thus should be considered the random component of seasonal hurricane activity, at least until further insights are gained. Indeed, when prediction algorithms are developed to forecast the annual number of Atlantic hurricanes, best hindcast skill results from models that assume a simple average for baroclinically influenced storms. These regression-based forecast models are only marginally better than climatology.

1. Introduction

Interannual variability of Atlantic-basin hurricane activity (where hurricane activity is defined by the number of hurricanes occurring in a season) has received considerable attention over the past several years. Some of the interest lies in the development of statistical models for forecasting this variability (e.g., Gray 1984; Gray et al. 1992, 1993, 1994; Elsner and Schmertmann 1993; Elsner and Hess 1993; Hess and Elsner 1994a). Current forecast skill is derived from variables having a direct relationship with the large-scale tropical environment, including the stratospheric quasi-biennial oscillation (QBO), El Niño Southern Oscillation (ENSO), as well as atmospheric anomalies over western Africa and over the Caribbean (Gray et al. 1992, 1993, 1994). This is to be expected since many Atlantic hurricanes have origins exclusively from synoptic-scale easterly waves in the Tropics. Hess and Elsner (1994b) provide a historical background to seasonal hurricane variability studies leading to the current suite of prediction models.

Hurricanes can form from other sources as well; it is sometimes observed, for example, that frontal intrusions from northern latitudes can provide the necessary organization for initiation of tropical depressions. Also, baroclinic activity can serve to rapidly intensify an otherwise benign tropical storm. It thus seems natural to consider whether recently discovered predictors are useful in forecasting baroclinically influenced hurricane activity. In fact, Hess and Elsner (1994a) showed a significant increase in hindcast skill when using extended-range prediction models to forecast hurricane activity formed solely from tropical influences.

The present work differs from this preliminary study of Hess and Elsner (1994a) in several important ways. First, since baroclinic disturbances can influence tropical cyclones at any stage in their development, we should eliminate not only hurricanes that originated from baroclinic systems, but also tropical cyclones that intensified into hurricanes as a result of baroclinic interactions. Second, both the extended-range (≈6-month lead) and short-range (≈0-month lead) prediction problems are considered. Third, the goal of this work is to develop prediction algorithms to forecast the seasonal number of all Atlantic-basin hurricanes and to demonstrate that such algorithms can outperform currently used prediction models.

The underlying hypothesis that baroclinically influenced hurricanes should be considered separately from tropical-only hurricanes when considering season to season variability depends critically on a good review of historical hurricane records in order to determine which storms were not affected at any stage of their development by baroclinic factors. The methodology used in stratifying Atlantic-basin hurricanes is pre-

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sented in section 2, followed by tests for statistical significance in section 3. Prediction models are described in section 4, with a summary and conclusion given in section 5.

2. Data and stratification

Data for this study were obtained from Atlantic tropical cyclone "best" track and intensity records made available by the National Hurricane Center (NHC) in Coral Gables, Florida, where best refers to an accurate assessment of storm location based on a postanalysis of all available data. The complete dataset extends back to 1886 and includes all tropical cyclones that reached tropical storm strength. Each storm includes latitude and longitude positioning and maximum sustained winds every six hours during the storm's existence. Data are most reliable after 1944 when the U.S. Air Force began aircraft reconnaissance missions to investigate individual storms over the Atlantic. All data for the period from 1886 to 1992 are available through anonymous FTP on metlab1.met.fsu.edu in directory /pub/elsner/Atlhurtracks. The current study uses this dataset over the period 1950–1992 and adds data from the 1993 season based on NHC's six-hourly track and intensity advisories for a total of 44 years.

As mentioned above, the current study is predicated on the idea that not all Atlantic hurricanes are the same; that is, hurricanes that form as a result of midlatitude baroclinic influences should be classified separately from hurricanes that form solely from tropical disturbances. Of course, this separation may not be important at all in forecasting future intensity or movement of individual storms, but in regard to forecasts of seasonal numbers such a segregation may be quite important. This idea is not entirely original; in fact, Gray (1968) found that tropical-cyclone development in portions of the Atlantic basin poleward of 20°N latitude takes place under different environmental conditions. As a result, earlier attempts at the kind of separation proposed here have relied on a strict latitudinal cutoff based on location of storm origin (Gray 1968). At the risk of introducing some screening errors, the present work uses a slightly more subjective approach in separating baroclinically influenced hurricanes from tropical-only hurricanes in order to better reflect the vagaries of hurricane development.

Stratification is done by examining the summaries of past tropical-cyclone seasons that have been published in *Monthly Weather Review* for the past several decades. These reviews describe the life cycle of each tropical storm by season. Typically the descriptions are adequate to clearly decide, for each hurricane, whether baroclinic influences were a factor or not. Seasonal summaries are particularly accurate after the use of satellite imagery beginning around the mid 1960s.

Decisions about baroclinic influences on tropical cyclone development are sometimes a bit speculative but especially before the use of satellite imagery. One of the authors (NEL) flew on many of the early, presatellite era reconnaissance missions for the NHC and was helpful in describing the synoptic situations of these earlier storms, including factors not necessarily mentioned in the *Monthly Weather Review* summaries. As an extra tool, daily synoptic charts in the period 1950–1970 were consulted whenever there were questions concerning a storm's status. Post-1970 *Monthly Weather Review* summaries are generally complete and reliable in the description of Atlantic tropical-cyclone activity.

It should be noted that storms that originated as easterly waves and reached tropical storm strength without midlatitude forcings but then became hurricanes after recurvature due to the storm's rapid acceleration ahead of an approaching trough in the westerlies are classified as being baroclinically influenced. As one example, Hurricane Flossie in 1978 began as an African wave and became a tropical storm as it moved across the Atlantic. Not until after recurving northward east of Bermuda did Flossie become a hurricane influenced by an approaching midlatitude frontal trough.

Results of the stratification are given in Table 1 where the numbers represent seasonal Atlantic-basin hurricanes for the two groups of tropical-only and baroclinically influenced storms. Baroclinically influenced hurricanes account for slightly more than one-

TABLE 1. Results of our stratification. Total number of hurricanes in a year is a sum of the tropical-only storms (column 2) and the baroclinically influenced storms (column 3).

	Annual number of hurricanes			Annual number of hurricanes	
Year	Tropical-only	Baroclinically influenced	Year	Tropical-only	Baroclinically influenced
1950	8	3	1973	1	3
1951	4	4	1974	3	1
1952	6	0	1975	4	2
1953	6	0	1976	1	5
1954	5	3	1977	0	5
1955	9	0	1978	2	3
1956	3	1	1979	2	4
1957	2	1	1980	4	5
1958	7	0	1981	4	3
1959	1	6	1982	0	2
1960	2	2	1983	0	3
1961	7	1	1984	0	5
1962	0	3	1985	4	3
1963	5	2	1986	0	4
1964	5	1	1987	1	2
1965	1	3	1988	4	2
1966	2	5	1989	5	2
1967	2	4	1990	4	4
1968	1	4	1991	0	4
1969	5	7	1992	0	4
1970	1	4	1993	1	3
1971	2	4	Total	125	130
1972	0	3	% of Total	49.0	51.0

half (51%) of all Atlantic-basin activity. Earlier studies have considered other components of seasonal tropical-cyclone activity, including the number of intense hurricanes. Intense hurricanes are storms having maximum sustained winds exceeding 50 m s^{-1}. The present stratification reveals that nearly 90% of all storms reaching intense hurricane strength had no baroclinic influence. This agrees with the results of Landsea (1993), who showed that the number of intense hurricanes is greater in wet Sahel years compared to dry years (i.e., when hurricanes are more likely to be rooted in the deep Tropics). Interestingly, our stratification results in a dataset that is similar to the one recently constructed by Avila and Pasch (1992) to include only hurricane activity originating from African waves. The difference is the current procedure eliminates hurricanes that, although originated as easterly waves, had noticeable development as a result of interaction with a baroclinic disturbance.

Another way to view the results of the stratification is to plot the location where each tropical cyclone reached hurricane strength for the two groups of baroclinically influenced and tropical-only storms (Fig. 1). As expected, the 20°N line of latitude offers a reasonable first guess at dividing the two groups, particularly over the eastern Atlantic. This simple division, however, is markedly flawed over the Caribbean and Gulf of Mexico where latitudinal independence of hurricane type is observed. Latitudinal dependence of storm type holds nicely over the open waters of the Atlantic but disappears in regions closer to the continents.

3. Statistical significance

a. Methodology

Since earlier studies have demonstrated forecast skill for the seasonal number of Atlantic hurricanes at various lead times, statistical significance of our stratification is tested by comparing predictive skill between forecasts made of the total number of hurricanes in a season to forecasts made of the number of hurricanes formed exclusively from tropical disturbances. An estimate of predictive skill is used as the test statistic. Statistical significance of the stratification is examined for both extended-range and short-range forecasts.

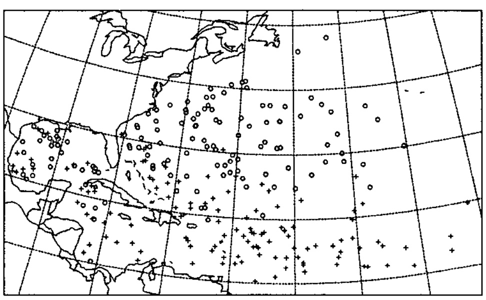

FIG. 1. Location where each of the 255 tropical storms over the period 1950–1993 reached hurricane strength for the two groups of baroclinically influenced (O) and tropical-only (+) hurricanes.

TABLE 2. Predictors used in the extended-range and short-range forecast models of this study.

Predictors independent variables	Forecast range: Extended	Forecast range: Short
RG-1	*	*
RS-1	*	
RS		*
U50	*	*
U30	*	*
|U50-U30|	*	*
ZWA		*
SLPA		*
SSTA		*
SOI		*

Table 2 shows the predictors used for both forecast ranges where RG-1 is the observed rainfall in the Gulf of Guinea from the previous year during August to November, except in the extended-range forecast where it is the current year. RS-1 is the observed rainfall in the Western Sahel from the previous year during August to September, except in the extended-range forecast where it is the current year. Also, RS is the observed rainfall in the Western Sahel during June and July. U50 and U30 are extrapolated values of the QBO of the zonal wind for September at 30 and 50 mb, and |U50-U30| is the magnitude of the vertical wind shear between these two levels in September near 10°N. SLPA is June–July anomalies of sea level pressures at selected stations in the Caribbean basin. ZWA is the June–July anomaly of the zonal wind at 200 mb over selected stations in the Caribbean basin. SOI and SSTA are El Niño predictors, where the SOI is the value of the Southern Oscillation index for June–July, and SSTA is sea surface temperature anomalies for the Central Pacific Ocean during June and July. Data for RG, RS, and SOI are expressed in terms of standardized deviations, while data for SLPA, ZWA, and SSTA are departures from the mean. Means for both standardized and anomaly variables are computed over the period 1950–1990. Data for the zonal wind variables (U50, U30, and |U50-U30|) are expressed in m s^{-1}. It should be noted that since hurricanes sometimes appear before 1 August, the dependent dataset, as appearing in Table 1, is modified slightly by removing the pre-August storms when using short-range prediction models. All of the above predictors where originally reported by Gray et al. (1992, 1994).

To get an idea of how the previously used predictors will be affected by the above stratification, a relative comparison of the value of Gulf of Guinea rainfall as a predictor for all hurricanes versus hurricanes formed solely from tropical influences is shown in Fig. 2. Hur-

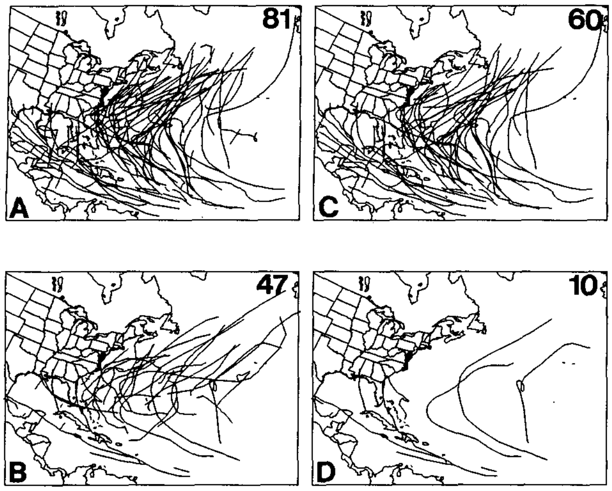

FIG. 2. Comparison of hurricane tracks for wet versus dry years based on Gulf of Guinea rainfall. (a) The 10 wettest years and all hurricanes; (b) 10 driest years and all hurricanes; (c) 10 wettest years and tropical-only hurricanes; (d) 10 driest years and tropical-only hurricanes. Number of hurricanes for each category are shown in the upper-right corner of each panel.

ricane tracks are plotted for the 10 wettest (top panels) versus 10 driest (bottom panels) for both tropical-only (right panels) and all (left panels) hurricanes. Total number of tracks are shown in the upper corner of each panel. Gulf of Guinea rainfall is a better indicator of tropical-only hurricanes than an indicator of all hurricanes as seen by the ratio of storms between wettest and driest years. This ratio increases from 2:1 in the case of all storms to 6:1 for the case of tropical-only storms.

To rigorously quantify the usefulness of the predictors for forecasting tropical-only hurricane activity, cross-validation hindcast exercises are employed. Cross validation (sometimes called jackkniving) attempts, with a limited data sample, to simulate actual forecast situations and thus provide an honest measure of an empirical procedure's ability to produce a skillful prediction rule. Predictive skill is the skill expected when the prediction rule, chosen by the procedure, is used in practice to forecast the future. Cross validation works by developing a separate prediction rule for each observation in the dataset based on the remaining observations. The other observations represent a fictitious reordering of "history" from which to predict the omitted observation, and the resulting "predictions" are termed hindcasts. A successful cross validation will remove the noise specific to each observation and assess how well the chosen procedure selects prediction rules when this coincidental information is deleted (Michaelsen 1987; Elsner and Schmertmann 1994).

An ordinary least-squares (OLS) multiple-linear regression algorithm is suggested in the present study. In-sample residual errors from the OLS regression are uncorrelated with all predictors, and there are no extreme outliers in the data. Thus it is expected that no advantage can be gained by using the least-absolute deviation (LAD) regression of previous studies (Gray et al. 1992, 1993, 1994). Hindcast skill is quantified by computing the product-moment correlation coefficient (r) between observed and cross-validated hindcasts. Since we are using regression models and are regressing about the mean of the distribution, there is no chance that the correlation coefficient will be a misleading indicator of model skill.

Cross validation in this context is the procedure for determining the coefficients of a particular class of models. Each hindcast in a cross-validation procedure is made with a different set of coefficients. Each is different because a different year has been completely removed, and the coefficients are estimated from the remaining years. Data from the year removed (independent data) cannot be used in any way to set the coefficients. If hindcast skill is acceptably high using this procedure, then what is accepted as a useful forecast algorithm is not a particular model (i.e., a single set of coefficients) but rather the entire class of models (in our case OLS linear regression). Since cross validation uses independent data, model skill estimated from a cross-validation exercise will often be considerably less than model skill estimated with in-sample (dependent) data but will more accurately reflect how the model will perform when making actual forecasts. This type of model-skill evaluation on independent data has not been done by Gray et al. (1992, 1993, 1994).

b. Results

Table 3 shows hindcast correlation coefficients for seasonal numbers of both tropical-only hurricanes and all hurricanes over both forecast ranges. As anticipated from the fact that model predictors characterize only the tropical environment, the reduced dataset, containing only hurricanes having formed exclusively from tropical disturbances, is better modeled than the total number of storms. This improvement in predictive skill for tropical-only hurricane numbers is consistent with evidence that during El Niño years and years of drought over the Sahel there is less tropospheric vertical wind shear (and perhaps more cyclogenesis) in regions poleward of 25°N latitude and in contrast to more shear (and less tropical cyclogenesis) equatorward of 20°N (Goldenberg and Shapiro 1993).

TABLE 3. Cross-validated hindcast correlation coefficients for tropical-only hurricanes and for all hurricanes for both forecast ranges.

Group	Extended-range	Short-range
Tropical-only hurricanes	0.82	0.81
All hurricanes	0.58	0.47

The question arises whether improvement in forecast skill as seen in Table 3 is simply a result of a reduction of the total numbers or the result of our careful stratification. In other words, would any arbitrary stratification, where the total number of hurricanes is reduced by the amount of the tropical-only set, increase the hindcast skill? The question forms a statistical null hypothesis and is tested by randomly permuting the reduction among the 44 years. Reductions are randomly assigned to the 44 years and subsequently subtracted from the total. If, for a given season, the reduction is greater than the total number, then a zero is assigned for that year. For each permutation OLS regression models are estimated on the randomly reduced dataset, and cross-validated hindcast correlation coefficients are computed. The procedure is repeated 10^4 times, and a tally is kept on how many times the randomly reduced dataset obtains specified correlation coefficients (Fig. 3). An arrow indicates the hindcast correlation coefficient obtained from regressing on seasonal numbers of tropical-only (i.e., carefully stratified) hurricanes. The increase in model skill is above what would be expected from a random reduction of the numbers for both extended- and short-range forecast periods; the null hypothesis that the stratification has no influence for seasonal predictability of hurricanes is rejected at a confidence level exceeding 99.9%.

4. Prediction algorithms

Having established that previously used predictors (West African rainfall, stratospheric winds, ENSO, and Caribbean temperature and pressure anomalies) are significantly more useful in explaining the variance of the seasonal number of tropical-only hurricanes, the question of how predictable are the seasonal numbers of baroclinically influenced hurricanes is addressed. It is possible that with a different set of regression coefficients, the same predictors, as found useful for forecasting the seasonal number of tropical-only hurricanes, might prove valuable for predicting the number of baroclinically influenced storms. To check this possibility the cross-validation exercise for computing hindcast errors is repeated using only the baroclinic storms. The hindcast correlation coefficient is only 0.14 for the seasonal number of baroclinically influenced hurricanes at the extended range and 0.07 at the short range. Obviously the tropical predictors, useful for explaining the seasonal variability of the number of tropical-only hurricanes, are largely irrelevant for linear regression forecasts of hurricane activity influenced by disturbances of midlatitude origin.

a. An extended-range model

Concerning the possibility of finding other predictors for explaining the number of baroclinically influenced hurricanes, we note that it does not appear physically

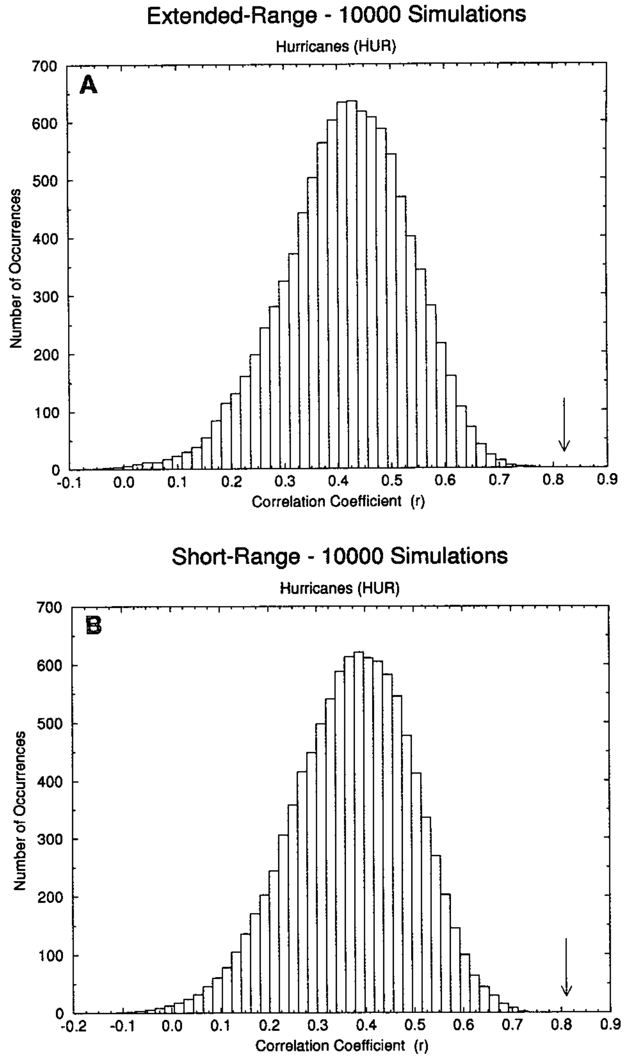

FIG. 3. Frequency graphs for the extended-range (a) and short-range (b) regression hindcasts of the randomly reduced seasonal number of Atlantic-basin hurricanes. The height of the bar represents the number of times the cross-validated correlation coefficient obtained the particular value on the horizontal axis. Arrows indicate correlation coefficients for the carefully screened tropical-only Atlantic-basin hurricanes.

plausible that any extended-range relationships would exist. This pessimism comes from the fact that the effective forecast range for midlatitude circulations is limited to the typical life span of baroclinic disturbances, which is on the order of weeks not months. Therefore, without any understanding of how long-wave circulation patterns over the midlatitudes during November of the previous year can influence circulation patterns 9–12 months later over the North Atlantic, no attempt has been made to search for additional predictors. Of course this does not preclude the possibility that one day a better understanding will ellucidate causal mechanisms that could guide a search for

TABLE 4. Cross-validated hindcasts of the seasonal number of Atlantic-basin hurricanes over the 44-yr period 1950–1993 using the proposed model for extended-range predictions.

	Number of hurricanes (Jan–Dec)			Number of hurricanes (Jan–Dec)	
Year	Observed	Hindcast	Year	Observed	Hindcast
1950	11	9.6	1972	3	3.6
1951	8	5.3	1973	4	3.8
1952	6	8.8	1974	4	5.8
1953	6	6.8	1975	6	6.4
1954	8	5.5	1976	6	4.1
1955	9	8.6	1977	5	5.0
1956	4	7.7	1978	5	4.4
1957	3	6.6	1979	6	3.3
1958	7	8.5	1980	9	7.4
1959	7	6.0	1981	7	5.4
1960	4	6.1	1982	2	1.9
1961	8	10.2	1983	3	3.7
1962	3	3.4	1984	5	0.9
1963	7	7.3	1985	7	5.4
1964	6	8.9	1986	4	5.2
1965	4	4.8	1987	3	4.3
1966	7	6.4	1988	6	9.7
1967	6	5.2	1989	7	7.1
1968	5	5.2	1990	8	7.4
1969	12	9.1	1991	4	3.5
1970	5	4.7	1992	4	3.6
1971	6	6.0	1993	4	3.5

midlatitude predictors. At present, however, it is conceded that for extended-range forecasts the number of baroclinically influenced hurricanes represents the random component of the total number of storms, at least with respect to linear regression models.

With this in mind, a prediction algorithm is proposed for forecasting the total number of Atlantic-basin hurricanes ($\hat{H}$) approximately six months in advance. The algorithm consists of an OLS linear regression model to forecast the number of tropical-only hurricanes ($\hat{H}_T$) to which we add a seasonal average number of baroclinically influenced hurricanes ($\bar{H}_B$). The model can be expressed as

$$\hat{H} = \bar{H}_B + \hat{H}_T,$$

where

$$\hat{H}_T = \gamma_0 + \sum_{i=1}^{5} \gamma_i x_i,$$

and where the γ_i's are coefficients on the five predictors listed in Table 2, with γ_0 as the constant term.

Performing a cross validation on this prediction algorithm results in a hindcast for each season (Table 4). The correlation coefficient between the observed number of hurricanes each year and the hindcast number of storms is 0.65 compared with 0.58 if the algorithm is more simply a regression to forecast the total number of hurricanes (traditional model). We refer to the approach of using a single regression-type model to forecast total activity as traditional because that is what has been done by Gray and colleagues and that is the current standard. Gray and company, however, employ least-absolute-deviation (LAD) regression instead of OLS, sometimes use rule-based models instead of regression, and have not, as mentioned previously, reported skill estimates based on independent data.

A comparison of results between these two forecast strategies and a comparison with climatology is given in Fig. 4. Plotted as an impulse for each number of hurricanes (H) is the number of years in which H hurricanes occurred. Superimposed on the impulses are the number of years in which the three prediction models produced the best hindcast. For example, during the period 1950–1993 there occurred five years in which the total number of hurricanes was three. Of those five years, our proposed model produced the best hindcast in four of them, with climatology performing best in the other year. In general our proposed model does best near the extremes of the distribution, with climatology and the traditional model performing better around the mean. Overall, skill above climatology is only marginal for both ours and the traditional model (see also Elsner et al. 1994).

b. A short-range model

In contrast to the extended-range prediction problem, for short-range forecasts it is more likely that additional predictors can be found for explaining the seasonal variability of the number of baroclinically influenced hurricanes. Indeed, it might be the case that midlatitude long-wave activity over the North Atlantic leads seasonal hurricane numbers by several weeks to

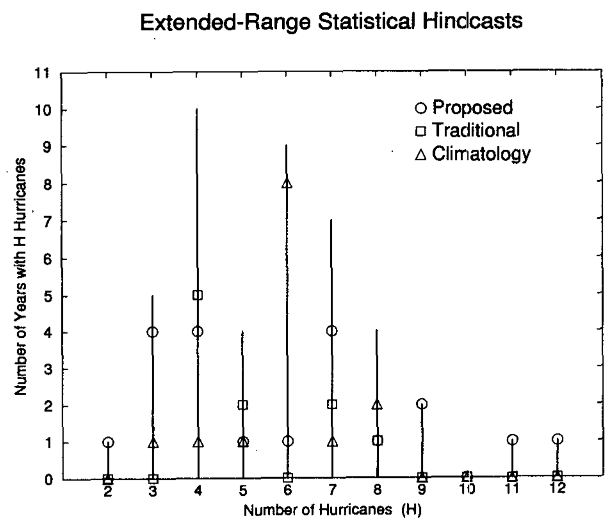

FIG. 4. Plot of the number of years in which exactly H hurricanes occurred (impulse) over the period 1950–1993. For each H the number of years in which the proposed model (circle), the traditional model (square), and the climatology (triangle) produce the best extended-range hindcast is plotted.

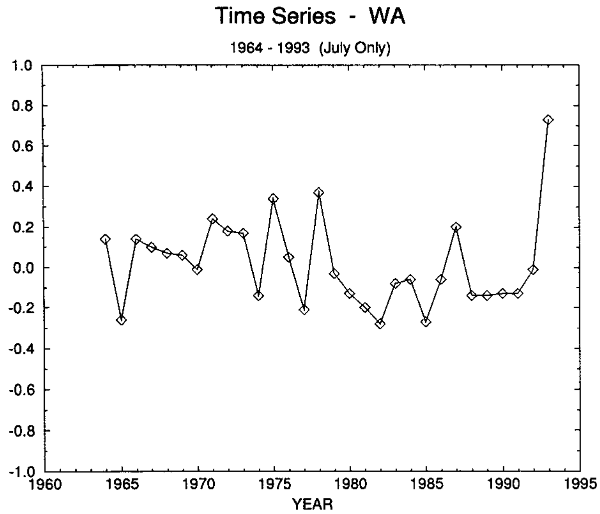

FIG. 5. Time series of the Western Pacific (WP) index for July (from Wallace and Gutzler 1981) over the period 1964–1993.

a month. Since the number of potential predictors is large, it is practical to consider summary variables. For this purpose it would be helpful if the summary variables represent the dominant modes of monthly variability. Numerous studies have described the Northern Hemisphere monthly variability, and for our work we have chosen the six indices developed by Wallace and Gutzler (1981). These indices describe the major oscillatory modes (centers of action) of the extratropical North Hemisphere, including the Pacific–North American (PNA), the western Atlantic (WA), the eastern Atlantic (EA), the western Pacific (WP), and the Eurasian (EU) patterns. There are actually a total of six indices because the PNA mode can be described by two different indices. Each index is constructed from 500-hPa height anomalies, and all are available via anonymous FTP on metlab1.met.fsu.edu in directory /pub/elsner/NH indices. As an example, July values of the WP index over the period are plotted in Fig. 5.

Simple (single predictor variable) regressions are used for short-range forecast modeling of the seasonal number of baroclinically influenced hurricanes. Cross-validated correlation coefficients for none of the six indices exceeds 0.09, and therefore it appears that, at least with respect to the major oscillatory modes of the NH midlatitudes and linear regression models, the seasonal number of baroclinically influenced hurricanes is the random component of total Atlantic hurricane activity. We have not done an exhaustive search for useful predictors of baroclinically derived tropical cyclones, and there is plenty of room for additional work in this area.

Similar to the extended-range forecast algorithm, our short-range algorithm for predicting the total number of hurricanes ($\hat{H}$) consists of an OLS linear regression to forecast the number of tropical-only hurricanes ($\hat{H}_T$) to which we add a long-term mean number of baroclinically influenced hurricanes ($\bar{H}_B$). As before, the model can be expressed as

$$\hat{H} = \bar{H}_B + \hat{H}_T,$$

where

$$\hat{H}_T = \beta_0 + \sum_{i=1}^{9} \beta_i x_i,$$

and where the β_i's are coefficients on the nine predictors listed in Table 2, with β_0 as the constant term. Cross-validated hindcast values from this model for each year are listed in Table 5. The correlation coefficient between observed and hindcast seasonal hurricane numbers is 0.60 compared to 0.47 if a regression is used to forecast all hurricanes. Comparisons of hindcast skill for the two modeling strategies and for climatology are shown in Fig. 6. Similar to results of the extended-range models, the present forecast strategy of incorporating the baroclinic-influenced hurricanes as a long-term average performs best. In particular it performs better than competing models on years with few and on years with many hurricanes. Again we note, however, that skill above climatology is only marginal.

5. Summary and conclusion

We have addressed the question of whether improvements in forecasting annual hurricane activity (as

TABLE 5. Cross-validated hindcasts of the seasonal number of Atlantic-basin hurricanes over the 44-yr period 1950–1993 using the proposed model for short-range predictions.

	Number of hurricanes (Aug–Dec)			Number of hurricanes (Aug–Dec)	
Year	Observed	Hindcast	Year	Observed	Hindcast
1950	11	8.7	1972	2	2.9
1951	7	3.5	1973	3	3.8
1952	6	7.6	1974	4	5.0
1953	6	7.3	1975	5	7.0
1954	7	5.0	1976	6	3.0
1955	9	9.5	1977	5	2.2
1956	3	6.4	1978	5	5.1
1957	2	6.2	1979	5	4.2
1958	7	7.3	1980	9	5.0
1959	4	4.0	1981	7	5.7
1960	3	6.8	1982	1	2.6
1961	7	9.2	1983	3	3.3
1962	3	4.1	1984	5	1.5
1963	7	6.6	1985	6	4.9
1964	6	10.1	1986	3	4.0
1965	4	2.8	1987	3	3.4
1966	3	5.7	1988	6	8.4
1967	6	6.0	1989	7	6.7
1968	3	3.3	1990	7	5.4
1969	12	9.9	1991	4	3.6
1970	4	4.2	1992	4	3.9
1971	6	4.8	1993	4	2.8

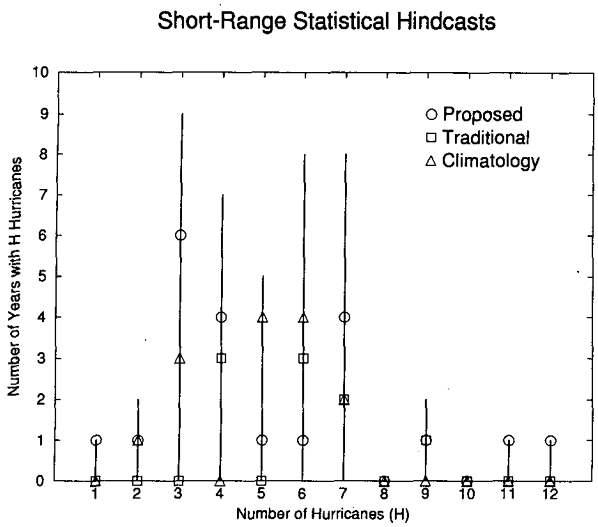

FIG. 6. Plot of the number of years in which exactly H hurricanes occurred after August first (impulse) over the period 1950–1993. For each H the number of years in which the proposed model (circle), the traditional model (square), and the climatology (triangle) produce the best short-range hindcast is plotted.

defined by the number of hurricanes occurring in a season) in the Atlantic basin are possible if hurricanes are separated according to factors affecting their origin and development. Hurricanes that form from tropical waves and develop without being directly influenced by baroclinic disturbances are considered tropical-only hurricanes, whereas all others are considered as baroclinically influenced storms. A careful separation of total annual numbers into these two groups for each season from 1950–1993 is made by consulting historical summaries as well as other sources.

We have demonstrated that the seasonal number of tropical-only hurricanes are significantly better predicted using previously identified tropical predictors compared with predictions of the seasonal number of all hurricanes. This stronger predictive relationship holds on both the extended-range and short-range timescale. It is also shown that these tropical predictors are worthless for linear regression forecasts of seasonal numbers of baroclinically influenced storms. Indices describing the dominant modes of Northern Hemisphere atmospheric variability are considered as potential predictors of baroclinic-influenced hurricane numbers with no success.

A prediction model is developed for forecasting seasonal hurricane activity using a two-prong approach. The number of tropical-only hurricanes is forecast using an OLS linear regression model, and a long-term mean is used as an estimate of the number of baroclinic-influenced hurricanes. This model is better at hindcasts of the seasonal number of hurricanes at both the extended and short ranges compared with hindcasts using the traditional approach of a single-regression equation on the sum of both hurricane types (see, e.g., Gray et al. 1992, 1993, 1994). Skill above climatology, however, remains only marginal. We conclude that any future study of seasonal hurricane activity over the Atlantic basin should consider tropical-only hurricanes as separate from hurricanes influenced by baroclinic disturbances.

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