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Recent developments in statistical prediction of seasonal Atlantic basin tropical cyclone activity

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ABSTRACT

Statistical forecasts of Atlantic basin seasonal hurricane activity have been issued since 1984 by the Tropical Meteorology Project at Colorado State University (CSU) headed by William Gray. Since these initial forecasts were developed, considerable improvements in data and statistical techniques have led to improved amounts of skill in both hindcasting and forecasting of seasonal Atlantic basin hurricane activity by CSU as well as other forecast groups including the National Oceanic and Atmospheric Administration and Tropical Storm Risk. Statistical seasonal forecasts derive their skill from atmospheric and oceanic parameters that span the globe.

Recent developments in statistical prediction include the development of shorter-period forecasts for the individual months of August, September and October and the issuing of landfall predictions or probabilities. Individual forecast groups generally utilize large-scale atmospheric wind and circulation patterns to issue their landfall forecasts. In addition, landfall probabilities down to the county level for all coastal counties from Brownsville, Texas to Eastport, Maine have recently been made available online. Several forecasting groups are now issuing seasonal forecasts for the Atlantic basin, and it is to be expected that the skill of these forecasts will continue to improve with additional access to improved data and modelling capabilities.

1. Introduction

Statistical prediction of seasonal tropical cyclone activity was first conducted in the Atlantic basin using research pioneered by Gray (1984a, b) at Colorado State University (CSU). Prior to 1984, there was no knowledge as to how active or inactive the upcoming Atlantic basin tropical cyclone season was likely to be. Seasonal forecasts for the Atlantic basin are considered important since the Atlantic basin has considerable year-to-year variability. For example, when evaluating the coefficients of variation (ratio of standard deviation to mean) for named storms from 1986 to 2005, the Atlantic basin's coefficient is nearly twice as large as the coefficient of variation for the East Pacific and almost three times as large as the coefficient of variation for the West Pacific. As an example of this considerable year-to-year variability, the 2005 tropical cyclone season had 27 named tropical cyclones, while 1972 and 1983 only had four named tropical cyclones. Eight major or intense hurricanes (category 3-4-5 on the Saffir–Simpson scale) (Simpson, 1974) occurred in 1950, while no major hurricanes were observed in 1968, 1972, 1986 and 1994.

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An extensive discussion of the prior research that led to the initial Atlantic basin statistical seasonal forecasts is presented in a review paper by Hess and Elsner (1994). Dynamical seasonal prediction of tropical cyclones is also now being attempted; however, it has yet to document skill at comparable levels to statistical techniques (Vitart and Stockdale, 2001). This paper discusses advances in statistical prediction for Atlantic basin tropical cyclones.

Initial seasonal predictions were issued in early June and early August beginning in 1984 by Gray and colleagues at CSU in Fort Collins, Colorado. They used statistical relationships between the El Niño – Southern Oscillation (ENSO), the quasi-biennial oscillation (QBO) and Caribbean basin sea level pressures with tropical cyclone activity in the Atlantic basin. When ENSO was cooler-than-normal, the QBO was in the west phase, and Caribbean basin sea level pressures were below normal, more tropical cyclones were predicted. The original forecasts used a rules-based formula where correction factors were added or subtracted depending on ENSO, QBO and Caribbean basin sea level pressure conditions. Initially, forecasts for the total number of named storms, named storm days, hurricanes and hurricane days were issued. It was a surprising discovery that the atmosphere/ocean had a long-period memory that enabled a skillful prediction of meso- to synoptic scale events, such as tropical cyclones, several months in advance.

The use of a Poisson regression model was suggested as a way to improve seasonal forecasting skill in the Atlantic basin for major hurricanes (Elsner and Schmertmann, 1993). They argued that since major hurricanes are a non-linear phenomena, a Poisson regression model was more appropriate. They demonstrated improvement in hindcast skill utilizing the Poisson technique. Additionally, it was suggested that prediction of tropical-only storms, that is, those that form purely from tropical waves, has greater skill than for all tropical cyclones (Hess et al., 1995). Since, Hess and Elsner (1994) have already discussed in extensive detail the developments in Atlantic basin seasonal hurricane forecasting up to 1994, this paper investigates developments in statistical forecasting since that point. Section 2 evaluates recent developments in seasonal prediction, Section 3 discusses developments in monthly prediction, and Section 4 examines recent work at predicting seasonal United States landfalls. Section 5 summarizes and concludes.

2. Recent improvements in Atlantic basin seasonal prediction

Seasonal hurricane predictions have continued to develop since the middle 1990s. Additional physical relationships were discovered which improved the hindcast skill of seasonal forecasts including the relationship between the Azores high and the upcoming season's hurricane activity. When the springtime Azores high is stronger than normal, it creates a self-enhancing feedback that increases trade wind strength and evaporation. This tends to cool sea surface temperatures in the upcoming summer (Knaff, 1998). The strength of this ridge in the previous October–November and the current March has a strong correlation ($\sim$0.5) with net tropical cyclone (NTC) activity during the upcoming Atlantic basin tropical cyclone season. NTC activity is calculated by summing the following six parameters normalized by their 1950–2000 climatological averages and dividing by six: named storms, named storm days, hurricanes, hurricane days, intense hurricanes and intense hurricane days (Gray et al., 1994). An average season accumulates 100 NTC units by definition.

The discovery of the relationship between the March Azores High strength and Atlantic basin tropical cyclone activity led to the issuing of forecasts in early April by the CSU research team along with their regularly scheduled forecasts issued in early December, early June and early August. An additional predictor that has been utilized by CSU in all their recent forecasts is the relationship between Atlantic basin sea surface temperatures and the upcoming hurricane season. In general, when waters in the tropical and North Atlantic are warmer, Atlantic basin hurricane seasons are more active (Dunn, 1940; Gray, 1968; Shapiro and Goldenberg, 1998; Goldenberg et al., 2001).

Early success showing operational skill in the issuing of seasonal hurricane forecasts for the Atlantic basin (Hastenrath, 1990) has led other groups to begin forecasting tropical cyclone activity as well. These additional groups include the United States federal government through the National Oceanic and Atmospheric Administration (NOAA) (began in 1998), Tropical Storm Risk (began in 1999) and the Cuban Institute of Meteorology (began in 1999). These groups use somewhat different methodologies for arriving at their final forecast values.

NOAA reviews a variety of predictors to make their seasonal predictions. Their forecast is based primarily on the observed state of the Atlantic multidecadal oscillation (AMO) and a forecast of ENSO from the Climate Prediction Center (CPC). In general, when the AMO is positive, vertical wind shear is reduced across the tropical Atlantic, sea surface temperatures are warmer across the tropical Atlantic and sea level pressures are lower across the tropical Atlantic indicating greater instability and enhanced low-level convergence (Goldenberg et al., 2001). All of these features associated with a positive phase of the AMO are more favourable for development of tropical cyclones in the tropical Atlantic and the Caribbean Sea. Figure 1 displays the strong positive correlation between the phase of the AMO and an Accumulated Cyclone Energy (ACE) index. ACE is defined to be the sum of the squares of the estimated 6-hr maximum sustained wind speeds for all systems when they have at least winds of tropical-storm strength (Bell et al., 2000).

A prediction of ENSO from the CPC is the other primary predictor that NOAA uses to issue its forecasts. The CPC utilizes a combination of currently observed conditions along with a variety of statistical and dynamical forecast models to issue its forecast for ENSO. The relationship between ENSO and Atlantic basin tropical cyclone activity has been well documented in the literature (Gray, 1984a; Goldenberg and Shapiro, 1996; Pielke and Landsea, 1999). In general, warm ENSO conditions are associated with anomalously strong vertical wind shear across the tropical Atlantic and subsidence in the Caribbean, while more favourable wind shear and vertical motion patterns are associated with cool ENSO anomalies.

NOAA also uses estimated August–October Atlantic basin sea surface temperatures based on persistence and a forecast by the Climate Forecast System (CFS) model (Saha et al., 2006). As discussed previously, warmer sea surface temperatures in the tropical Atlantic generally indicate increased likelihood for an active Atlantic basin hurricane season. A final predictor that NOAA utilizes is a forecast from the CFS model for August–October vertical wind shear across the tropical Atlantic (Chelliah and Saha, 2004). Large amounts of vertical wind shear are detrimental for hurricane development and intensification (Gray, 1984a; Frank and Ritchie, 2001; Knaff et al., 2004). NOAA's final forecast is derived from this predictor information and qualitatively adjusted by a consensus of forecasters located at several centres including the CPC, the National Hurricane Center and Hurricane Research Division (see http://www.noaa.gov for more information on NOAA's forecasts). NOAA issues predictions for the total number of named storms, hurricanes and major hurricanes expected to form in the Atlantic basin in a particular year. They also issue a prediction for the ACE index.

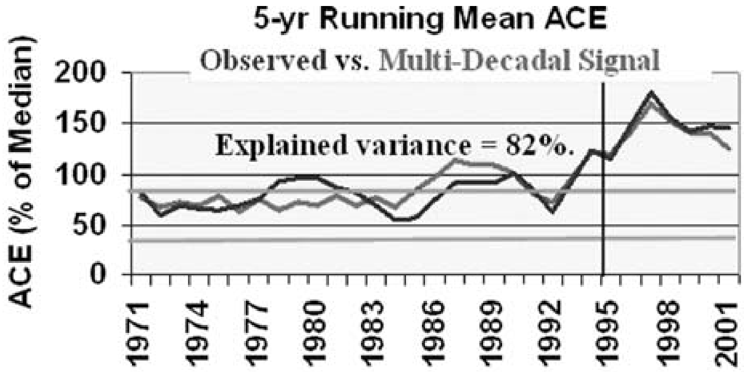

Fig. 1. Five-year running mean ACE (dark line) plotted against a measure of the Atlantic Multidecadal Oscillation (AMO) (light line). Note the strong measure of agreement between the two lines. Adapted from Bell and Chelliah (2006).

Tropical Storm Risk (TSR), a private forecasting consortium based out of the United Kingdom, utilizes a methodology that predicts August–September trade wind speeds in the Caribbean and the tropical North Atlantic (7.5°N–17.5°N, 30°W–100°W) and August–September sea surface temperatures in the tropical North Atlantic (10°N–20°N, 20°W–60°W) (M. A. Saunders, 2006, personal communication). From this prediction of trade wind speeds and sea surface temperatures, they arrive at a forecast for Atlantic basin tropical cyclone activity.

TSR's forecast of trade wind speeds is calculated from two predictors (M. A. Saunders, 2006, personal communication). The first predictor is an August–September ENSO prediction based on a modified version of the ENSO–CLIPER model (Knaff and Landsea, 1997). Sea surface temperatures are predicted for the tropical Pacific from 5°S to 5°N, 160°E to 90°W. The second predictor is a prediction of Atlantic/Caribbean sea surface temperatures from 7.5°N to 17.5°N, 40°W to 85°W. Atlantic/Caribbean sea surface temperatures are calculated from a 1-month lagged principal component analysis of North Atlantic sea surface temperature (SST) variability for the region from 0° - 50°N, 0° - 100°W (excluding the Pacific Ocean).

TSR's prediction of August–September tropical North Atlantic sea surface temperatures (10°N–20°N, 20°W–60°W) is derived from the same one-month lagged principal component analysis technique mentioned in the previous paragraph. From these two predictors, TSR issues forecasts for the total number of named storms, hurricanes, and major hurricanes as well as the ACE index for the entire Atlantic basin. Utilizing these same two predictors, they also issue a forecast for the total number of named storms, hurricanes, major hurricanes and ACE expected in the main development region (defined as 10°N–20°N, 20°–60°W), the Caribbean Sea and the Gulf of Mexico (see http://tsr.mssl.ucl.ac.uk for more information on TSR's forecasts).

TSR's hindcasts and forecasts have shown considerable skill when compared with climatology. Figure 2 displays improvement in mean-squared error (MSE) of TSR's forecasts of the ACE index for the entire Atlantic basin using hindcast data from 1984 to 2001 and real-time forecast data from 2002 to 2005 compared to a previous 10-yr mean forecast. The scheme shows skill from early December with improving skill as the hurricane season approaches. It improves on the previous 10-yr mean by approximately 30% in early June and by over 60% in early August using MSE as the skill metric.

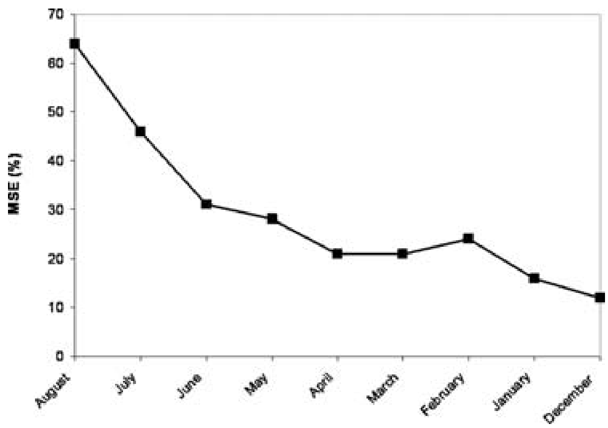

Fig. 2. Tropical Storm Risk skill for the Atlantic basin ACE index (1984–2005) based on hindcasts (1984–2001) and forecasts (2002–2005). Skill is relative to mean-squared error (MSE) and is the percent improvement of the hindcast/forecast over the previous 10-year mean.

The Cuban Institute of Meteorology utilizes a linear regression methodology involving several predictors to issue its forecast for the Atlantic basin hurricane season. The predictors that they utilize are quite similar to the predictors utilized by the other forecast groups already discussed including sea level pressure and sea surface temperature values in the tropical Atlantic as well as the observed state of the QBO and the observed and predicted state of ENSO. In addition, the Cuban Institute of Meteorology also predicts the activity likely to develop in the Caribbean Sea, since this is the area that is of greatest interest to individuals living in Cuba (see http://www.met.inf.cu for more information on the Cuban Institute of Meteorology forecasts).

The development of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis has provided a wealth of historical

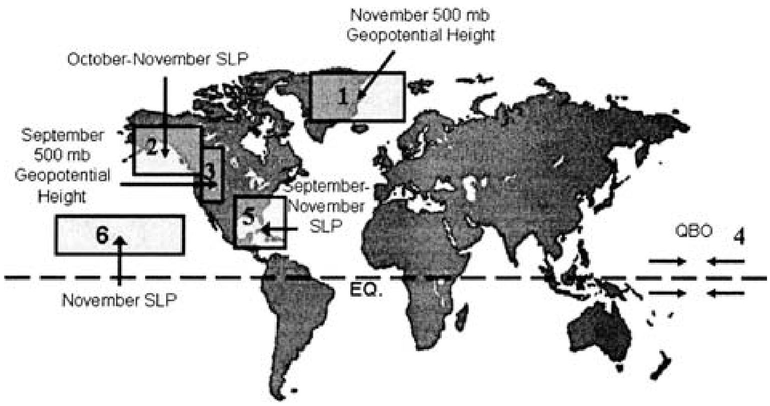

Fig. 3. Map of predictors used in the new early December statistical forecast for the following year's Atlantic basin hurricane season, reproduced from Klotzbach and Gray (2004).

data that is available for use in statistical climate prediction (Kalnay et al., 1996; Kistler et al., 2001). A new early December forecast scheme using the reanalysis was implemented by Klotzbach and Gray (2004). A map of the predictors used in the new early December forecast is shown in Figure 3. The recent failure of African rainfall predictors had diminished the forecast skill of the earlier December forecast scheme (Gray et al., 1992). Comparable hindcast skill between the two forecast schemes was shown and eliminated the potentially error-prone African rainfall measurements. Approximately 45% of the cross-validated variance can be explained for NTC activity based on 52 yr of hindcasting (1950–2001) (Klotzbach and Gray, 2004). Cross-validation for this forecast scheme was done by using a jack-knife technique. That is, the regression estimate for an individual year was calculated by omitting the observation being predicted when developing the forecast equation for that particular year. In addition, following the suggestion of Elsner and Schmertmann (1993), the new December forecast scheme implemented a Poisson regression model for prediction of major hurricanes. The level of hindcast skill with this new early December forecast scheme is remarkable considering that these hindcasts are issued seven months before the start of the hurricane season.

Another recent development in seasonal prediction is the use of analogue prediction techniques. This involves searching for years in the past that have conditions similar to what is currently observed and what is expected to occur during the upcoming hurricane season. For example, in the June 2005 forecast, researchers looked for years with warm Atlantic basin sea surface temperatures and neutral ENSO conditions. Then, the amount of activity that occurred during the four or five best analogue years is computed, and these analogue results are compared with the statistical forecast before a final forecast is issued. Full documentation of the CSU analogue forecasting technique is available online (see http://hurricane.atmos.colostate.edu). Both statistical and analogue forecasts are consulted before a final adjusted forecast is made by the Tropical Meteorology Project at CSU. The final adjusted forecast has shown the most skill for the Tropical Meteorology Project since forecasts began in 1984 (Owens and Landsea, 2003).

3. Monthly Atlantic basin prediction

A recent development in statistical tropical cyclone prediction is the prediction of an individual month's tropical cyclone activity. These shorter-term predictions are issued due to the fact that inactive seasons can have active months, and active seasons can have inactive months. For example, in 2004, August–September had activity at record levels; whereas, October activity was somewhat below normal. Individual monthly prediction began with a prediction of August-only activity issued with the 1 August seasonal forecast in 2000. The August monthly forecast has been developed further over the past few years (Blake and Gray, 2004). The forecast showed considerable skill in hindcast mode (explaining nearly two-thirds of the cross-validated variance in NTC activity over the hindcast period of 1949–1999). The forecast has been issued in real-time over the period 2000–2006, and from 2000 to 2005, the forecast improved upon the previous five-yr monthly mean for NTC activity by 38% (using MSE as the skill metric). The August-only forecast was not successful in 2006. Figure 4 displays observed and predicted values of NTC for the August-only monthly forecast from 2000 to 2006.

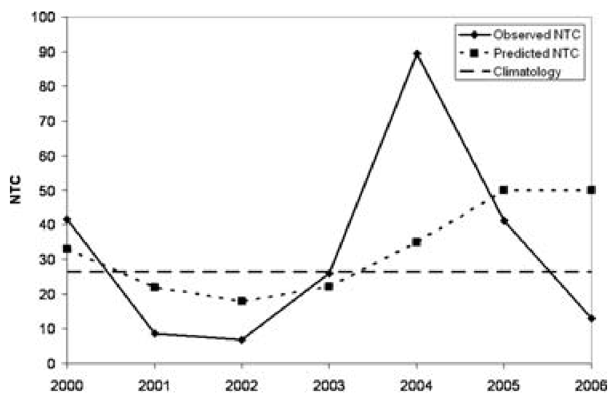

Fig. 4. Time series showing predicted (short dashed line) August NTC versus observed NTC (smooth line) for 2000–2006. The long dashed line is the August NTC climatology (calculated from 1949–1999).

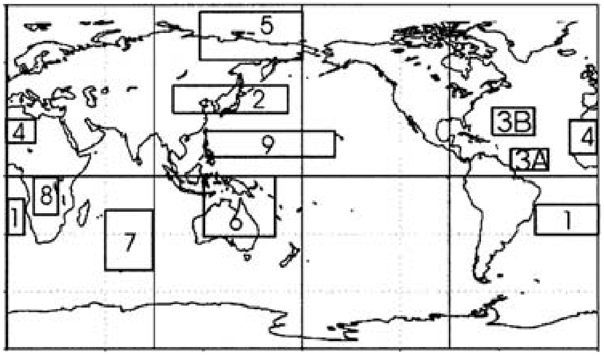

Fig. 5. Location of predictors used in the 1 September forecast for September Atlantic basin tropical cyclone activity, reproduced from Klotzbach and Gray (2003).

Following the success of the August-only forecast, a September-only forecast was developed and debuted with the 1 August seasonal forecast in 2002. The September-only forecast has also been developed further over the past few years (Klotzbach and Gray, 2003). September monthly forecasts are issued in early August and then updated in early September to reflect any potential changes in atmosphere/ocean conditions. The September-only forecast uses different predictors from the August-only forecast, which is to be expected considering that the formation region for tropical cyclones in September is somewhat different from where it is during August. The likely formation region for tropical cyclones in September is expanded considerably from August, with tropical cyclones often forming in the eastern tropical Atlantic during the month of September. In August, storms tend to cluster closer to the Leeward and Windward Islands (Neumann et al., 1999). In addition, more tropical cyclones tend to form at higher latitudes during September. Figure 5 shows the predictors that are utilized for the 1 September forecast of September monthly activity. Comparable hindcast skill to the August-only forecast was demonstrated over the period from 1950 to 2000. Both the August and September forecast schemes may have been somewhat over-fit to the data, that is, there may be too many predictors utilized to predict each individual tropical cyclone parameter (i.e. named storms, named storm days, etc.). A more realistic evaluation of hindcast skill is to evaluate the skill of these forecasts using the three best predictors for August and September NTC, respectively. Fifty-nine percent and 61% of the cross-validated variance is explained for NTC using the three best predictors for the August and September forecasts issued on the start of each month (i.e. 1 August and 1 September, respectively) (Blake, 2002; Klotzbach, 2002). This level of hindcast variance explained is still quite high for a subseasonal prediction.

An October-only forecast has also been developed and was issued beginning with the 2003 season. The initial October monthly forecast is issued in early August and then updated in early September and early October to reflect potential changes in atmospheric and oceanic conditions. Comparable hindcast skill to the August and September monthly forecasts is achieved when evaluating skill by the cross-validated variance explained by the NTC activity metric. Documentation of the October-only forecast is available online at the Tropical Meteorology Project's website (see http://hurricane.atmos.colostate.edu).

4. United States landfall prediction

The issuing of landfall probabilities with seasonal forecasts began with the CSU forecast team and their August 1998 forecast (Gray et al., 1998). These probabilities were based upon a forecast of NTC activity and a measure of North Atlantic SSTA*. In general, when an active hurricane season is predicted (high NTC), more tropical cyclones make United States landfall than when fewer tropical cyclones are predicted. For example, as Figure 6 shows, there is a 10 to 2 ratio of major hurricanes making landfall along the United States East Coast when comparing the top 15 December NTC + SSTA* hindcasts with the bottom 15 December NTC + SSTA* hindcasts (Klotzbach and Gray, 2004).

SSTA* is a weighted measure of the past 6 yr of North Atlantic sea surface temperatures calculated from the NCEP/NCAR Reanalysis and is defined as follows:

$$\mathrm{SSTA}^* = \overline{SSTA}_6 + {}^1\!/_2\left(\overline{SSTA}_1\right) + {}^1\!/_4\left(\overline{SSTA}_{2-1}\right), \quad (1)$$

where SSTA* is a measure of North Atlantic sea surface temperature anomalies in the region (50°–60°N, 10°–50°W) expressed in 10^{-2}°C, $\overline{SSTA}_6$ is the average mean North Atlantic SST anomaly over the past 6 yr, $\overline{SSTA}_1$ is the mean SST anomaly of the last year, and $\overline{SSTA}_{2-1}$ is last year's July–November SST anomaly minus last year's January–June SST anomaly. To arrive at an NTC + SSTA* value for a particular forecast, the process is as follows: (1) Predict an NTC value (say 150%); (2) Calculate the SSTA* deviation (say +0.32°C); (3) Add the two numbers together ($150 + 32 = 182$). Therefore, in this particular example, the NTC + SSTA* value would be 182.

When SSTA* values are above average, there is an increased risk of landfall on the United States coastline and especially along the East Coast. Warm North Atlantic sea surface temperatures are indicative of an active phase of the AMO (Goldenberg et al., 2001) and a likely strong phase of the Atlantic thermohaline circulation (Gray et al., 1996; Latif et al., 2004). In general, when the AMO is positive, conditions in the Atlantic are more favourable for hurricane genesis and intensification. Conditions that become more favourable with a positive phase of the AMO include increased sea surface temperatures and reduced vertical wind shear in the tropical Atlantic and Caribbean (Bell and Chelliah, 2006).

The CSU Tropical Meteorology Project used a combination of NTC and SSTA* to issue forecasts of landfall probability for the entire United States coast, the East Coast, and the Gulf Coast. In addition, probabilities were calculated for 11 regions

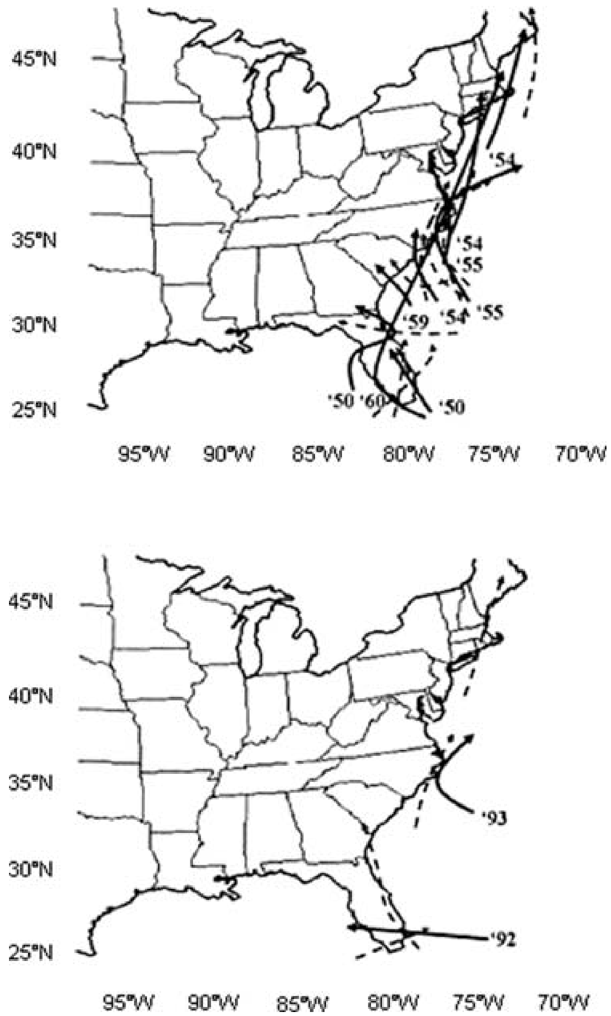

Fig. 6. (top) Landfalling tropical cyclones for the 15 highest cross-validated hindcast NTC + SSTA* values and (bottom) landfalling tropical cyclones for the 15 lowest cross-validated hindcast NTC + SSTA* values, respectively, along the U.S. East Coast for the early December hindcast. Category 1+2 hurricanes are the dashed lines, and category 3-4-5 hurricanes are the solid lines. Years of landfalling major hurricanes are as indicated. Ten major hurricanes made landfall in the top 15 hindcasts, with only two major hurricanes making landfall in the bottom 15 hindcasts. Adapted from Klotzbach and Gray (2004).

from Brownsville, Texas to Eastport, Maine, where the eleven regions were created based upon major hurricane landfall frequency during the 20th century (Fig. 7). Climatological landfall probabilities were calculated from landfall data provided by the National Hurricane Center, and these probabilities were then adjusted by the latest forecast NTC and SSTA* values. The recent reanalysis of hurricane landfall intensities from 1851 to 1914 by the Hurricane Research Division and collaborators have been included in the landfall statistics database (Landsea et al., 2004). Due to fairly sparsely populated coastals in the latter part of the 19th century along the Gulf Coast and Florida Peninsula,

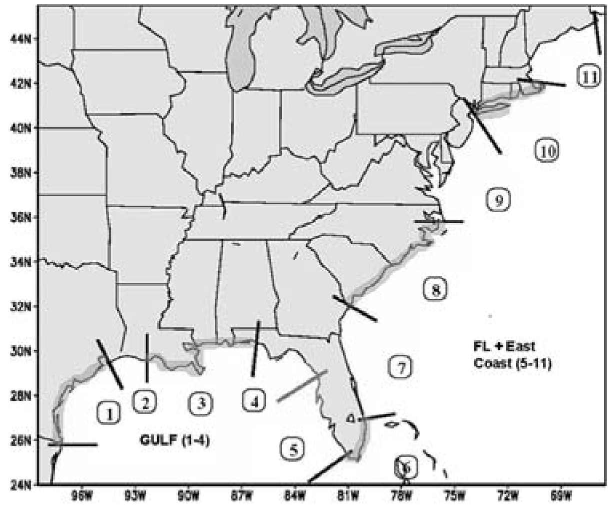

Fig. 7. The eleven regions for which the Tropical Meteorology Project issues landfall probabilities, reproduced from Gray et al. (2001). The shaded regions were hit much more frequently by major hurricanes during the 20th century.

climatological probabilities have been calculated from 1880 to 2004 for Regions 1–4 and Region 7, with probabilities being calculated from 1900 to 2004 for Regions 5 and 6. Probabilities for Regions 8–11 are calculated from 1851 to 2004.

More recently, the Tropical Meteorology Project at CSU has put its landfall probabilities online in an interactive mapping format (see http://www.e-transit.org/hurricane). Probabilities for the 11 regions discussed above are available online. These probabilities are further subdivided into 55 subregions and 205 coastal and near-coastal counties from Brownsville, Texas to Eastport, Maine. Since there are only 100–150 years of reliable landfall data, probabilities for smaller areas are calculated based off the landfall probabilities for the region. The region probability is multiplied by the ratio of the coastline distance of the subregion or county divided by the coastline distance of the region. Subregions were created based upon population density. In addition to landfall probabilities, the web application also provides vicinity probabilities and 50-yr probabilities. Vicinity probabilities attempt to take into account the considerable uncertainty in track and intensity prediction, and 50-yr probabilities of landfall are provided to give individuals a better idea of the long-term likelihood of being affected by a tropical cyclone.

Beginning with the December 2006 forecast for the 2007 season, CSU has suspended use of the SSTA* parameter for issuing landfall probabilities. Upon more rigorous statistical testing, SSTA* does not appear to add additional skill beyond that supplied by NTC.

Another group that predicts landfalling tropical cyclone activity is TSR. Saunders and Lea (2005) have recently demonstrated that there is statistical skill (approximately 50% of the variance in hindcast mode from 1950 to 2003) in forecasting a United States landfalling ACE (US ACE) index by August 1. The US ACE

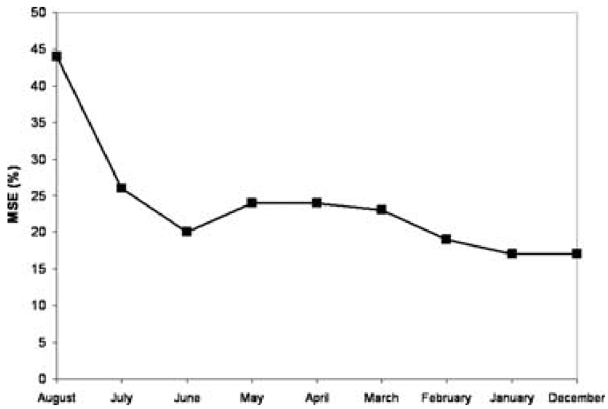

Fig. 8. Tropical Storm Risk skill for the US ACE index (1984–2005) based on hindcasts (1984–2001) and forecasts (2002–2005). Skill is relative to mean-squared error (MSE) and is the percent improvement of the hindcast/forecast over the previous 10-year mean.

index is defined to be the sum of the squares of the hourly maximum sustained wind speeds (in units of knots) from all tropical cyclones, including those that have transitioned to extra-tropical, that have winds of at least tropical storm strength (Saunders and Lea, 2005). This US ACE index is then reduced by a factor of six to be in keeping with the ACE index developed by NOAA (Bell et al., 2000). The US ACE index is shown to be moderately correlated with total damage caused by landfalling tropical cyclones along the United States coast. Figure 8 displays improvement in MSE of TSR's forecasts of the US ACE index using hindcast data from 1984 to 2001 and real-time forecast data from 2002 to 2005 compared to a previous 10-yr mean forecast. The use of a 10-yr mean forecast is indicative of inter-decadal variability that has been well documented to exist in Atlantic basin hurricane activity (e.g. Goldenberg et al., 2001). The use of a 10-yr mean is analogous to the technique of optimal climate normals that is currently being utilized at the CPC for temperature and precipitation prediction (Huang et al., 1996). The scheme shows skill from early December with improving skill as the hurricane season approaches. It improves on the previous 10-yr mean by approximately 20% in early June with skill improving considerably to approximately 45% in early August using MSE as the skill metric.

The US ACE forecast utilizes a combination of six height-averaged 925 to 400 mb zonal winds obtained from the NCEP/NCAR reanalysis as its predictors. When the prediction for the US ACE index is above normal, the Bermuda High tends to be strengthened and displaced to the north of its climatological position. A stronger and northward-displaced Bermuda High in August–September drives cyclones further westward across the United States coastline and inhibits recurvature. The model has been quite successful in forecast mode over the 2004 and 2005 seasons, predicting active landfall seasons to a high probability (Lea and Saunders, 2006). According to the authors of that study, if the insurance industry acted upon these forecasts over a period of several years, they could improve upon their return by up to about 30% (Saunders and Lea, 2005).

5. Conclusions

Statistical prediction of Atlantic basin tropical cyclones has developed considerably since it began in the early 1980s. It was initially a surprising discovery that the atmosphere and ocean had a long-term memory that allowed for prediction of the frequency of Atlantic basin meso-scale tropical cyclone events many months in advance. This discovery has led to the discussion and description of physical relationships between many large-scale ocean/atmosphere features and Atlantic basin tropical cyclones (i.e. ENSO, QBO, Atlantic basin sea surface temperatures and sea level pressures). In addition to seasonal forecasts, predictions are now made for the individual months of August, September and October. A large amount of research has also been invested in the issuing of landfall probabilities and forecasts, and these have also shown considerable skill in both hindcasts and real-time forecasts. As global data sets, such as the NCEP/NCAR and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis products continue to be refined and enhanced, the skill of statistical forecasts of tropical cyclone activity will likely continue to improve.

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