NORTH ATLANTIC OCEAN BASIN TROPICAL CYCLONE ACTIVITY AS RELATED TO CLIMATE FACTORS FOR THE 2010 HURRICANE SEASON

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Atmospheric and oceanic climate factors and conditions play a crucial role in modulating seasonal/annual tropical cyclone activity in the North Atlantic Ocean Basin. In the following, correlations between North Atlantic tropical cyclone activity including frequency of occurrence and pathways are explored, with special emphasis on hurricanes. The value of two-dimensional and three-dimensional data sets representing climate patterns is investigated. Finally, the diagnostic study of historical tropical cyclone and hurricane temporal and spatial variability and relationships to climate factors lead to a statistical prognostic forecast, made in April, 2010, of the 2010 tropical cyclone and hurricane season. This forecast is tested both retrospectively and presently and is shown to be quite accurate. Knowing the probability of the frequency of occurrence, i.e. the
numbers of named storms to form in general and the number of hurricanes (NHs) that are likely to form, is important for many societal sectors. However, the reliable forecasts of probable pathways of predicted events, specifically the likely NH landfalls along the coastlines of the United States, should have great potential value to emergency planners, the insurance industry, and the public. The forecast provided in this study makes such a prognostication. As the 2010 hurricane season has progressed, an update of the goodness of the forecast is shown to be quite accurate in numbers of named events, hurricanes, major hurricanes (MHs), and landfalls. The mathematical and statistical methodology used in this study, which could be coupled to next generation “empirical modal decomposition,” suggests that this may signal a new era in the future of tropical cyclone forecasting, including the reliable prognostication of numbers of events, intensities of events, and the pathways of those events. The ability to reliably predict the probability and location of landfalls of these destructive events would be very powerful indeed.

Keywords: Tropic cyclones; hurricane; landfalls frequency; forecast; north Atlantic ocean basin; sea surface temperature; climate; vertical shear; sea level pressure; geo-potential height; EOF; EMD.

1. Sea Surface Temperature (SST) Anomalies in the Atlantic Ocean Basin

Tropical Atlantic sea surface temperature (SST) has been found to have a direct thermodynamic effect on tropical cyclone formation through its influence on moist static stability via evaporation-wind feedback [Malkus and Riehl, 1960]. Shapiro (1982) and Gray (1984) concluded that SST indirectly alters the vertical wind shear (VWS) through a strong inverse relationship with surface pressure. Mo et al. (2001) suggested that both Atlantic tropical storm activity and Western Africa rainfall are influenced by the Atlantic SST anomaly (SSTA). The above normal SSTA generates favorable atmospheric conditions for tropical storms to develop and trigger a wet monsoon season over the Sahel region. It is well known that SSTs must be sufficiently warm for tropical disturbances to form and persist. On the other hand, spatial distribution of the Atlantic SSTAs is also closely related to tropical cyclone-intensity and track patterns. [Wendland (1977)] found that the area of the North Atlantic Ocean with SSTs exceeding 26.8°C is directly (nearly exponentially) related to the frequency of tropical cyclones. When the mean monthly area of warm SSTs is less than 8.5 x 10^6 km^2, tropical cyclones do not readily occur. The correlation between North Atlantic accumulated cyclone energy (ACE) and monthly Atlantic SST (averaged from May to September) are calculated using 60 years (1950–2009) ACE and 2-D SST data on each 2 x 2 grid point. Figure 1 shows a firm and significant correlation zone distributed in most portion of the western Atlantic. This correlation is especially significant along west coast of North Africa (white circle).

The horse-shoe shaped pattern linked primarily to cooling in SST due to the passage of hurricanes, where energy (heat) was carried out from ocean and distributed to atmosphere. In other word, the upper tropics in the middle and western Atlantic provides major energy for hurricane to develop and intensify. An inverse relationship is identified between North Atlantic ACE and South Atlantic SSTAs.
This relationship is significant at bottom right portion of the study domain with correlation coefficient greater than 0.4 (99% CFL).

The anomalous SST in North Atlantic also demonstrates significant positive correlation with North Atlantic major hurricane (MH) count as shown in Figs. 2(a) and 2(b). In May and June, a very high correlation centered around 10°W–22°W, 22°N–42°N is identified, from which a predictor time series can be extracted.

Correlations between U.S. East Coast landfall (ECLF) and Atlantic anomalous SST in January–February and July–September are displayed in Figs. 3(a) and 3(b). A significant correlation zone is located in low tropical/subtropical south Atlantic (20°S–40°S, 20°W–40°W) in January–February and July–September (20°S–50°S, 20°W–10°E). In North Atlantic, a significant positive correlation zone is identified in January (40°N–60°N, 10°W–40°W) and July–September (35°N–45°N, 10°W–20°W), correlations in the circled area exceed the 95% CFL.

Figure 4(a) and 4(b) shows the composite SSTAs in January–February for ≥2 landfall years (Figs. 4(a)) and no landfall years (Figs. 4(b)). One distinct difference is that above normal SST occupies the MDR during the high-frequency landfall years, while below-normal SST is observed in those none-landfall years. A warm core is positioned in northeast portion of the North Atlantic during high-frequency landfall years and a dipole can be seen in the North/South Atlantic Basin. In non-landfall years, however, the northern warm core has shifted to middle-west North Atlantic, and a tripole SSTA structure is identified. Similar SSTA structures are observed from July to October (Figs. 5(a) and 5(b)).
Changes in the SST distribution patterns result in changes in sea level pressure, the subtropical high location, and zonal/meridional winds, and, therefore, further influence North Atlantic hurricane track patterns.

2. Vertical Shear of Horizontal Wind in the North Atlantic

Active hurricane seasons in the Atlantic Basin are generally associated with a reduction of VWS between 850mb and 200mb in North Atlantic, especially within
the critical 10°N to 20°N latitude belt stretching from North Africa to Central America, termed Main Development Region (MDR) [Gray et al., 1993], which is strongly related to ACE and MH counts [Landsea (2000); Yan (2006)]. It must be sufficiently weak for tropical disturbances to form and persist. Strong VWS
Anomalous SST (January-February) associated with ≥ 2 landfall years

Anomalous SST (January-February) associated with no landfall years

Fig. 4. Anomalous SST (January–February) in (a) ≥ 2 landfall years and (b) non- or zero landfall years.

usually inhibits the formation and intensification of the hurricanes by preventing the axis-symmetric organization of deep convection. During August–October, VWS in the Atlantic basin’s MDR normally exhibits a strong westerly component and exceeds the critical 7.5–10 m/s threshold for hurricane formation [Gray et al., 1993]. This large shear is caused by a combination of upper level (200 hPa) westerly winds in association with a mean tropical upper tropospheric trough [Sadler, 1976], and low level (850 hPa) easterly trade winds. Thus, very active hurricane seasons require that the VWS in this region to be substantially reduced from the
climatological mean. Figure 6(a) demonstrates a very strong negative correlation band (0°N–20°N) between North Atlantic MH count and averaged VWS in tropical North Atlantic from July to September. The negative band extends westward to East Pacific, and eastward to middle Africa mainland. Adjacent south to this negative band, a positive correlation band occupies the low south tropical Atlantic (2°S–20°S), and a negative correlation band occupies 20°S–40°S, followed by a positive band south of 55°S.
Fig. 6.
Figure 6(b) shows the correlation between ACE and vertical shear, which has similar structure as Fig. 6(a). The above facts indicate that the VWS–hurricane relationship holds not only in MDR as reported previously, but the whole tropical regions as well. The best correlation domain is not in MDR, but the north portion of South American continental.

Previous studies have revealed that VWS in MDR is one of the most important pre-conditions for NA cyclongenesis [Gray et al., 1993; Landsea, 2000]. Our study shows that the vertical shear in the whole low tropical Atlantic (0°N–18°N) demonstrates significant correlation with NA hurricane activity. The best correlation domain is not in MDR, but located around South America continental (dotted circle). One reason is due to zonal wind consistency — wind system in low tropic is relatively stable; another reason is the formation and passage of tropical cyclone in MDR may destroy the vertical wind structure.

3. Sea Level Pressure in the Atlantic Ocean

Low sea level pressure in tropical North Atlantic is favorable for hurricane formation. Under the influence of above-normal surface pressure over the development areas of the North Atlantic basin, cooler and drier conditions typically prevail in the atmospheric boundary layer, which is linked to larger vertical shear of the horizontal wind, prohibits the hurricane initiation and growth [Knaff, 1997]. The pressure difference between Azores and Iceland represents the dominant pattern of atmospheric circulation variability over the North Atlantic, known as North Atlantic Oscillation (NAO), which linked to change in the surface westerlies across the Atlantic onto Europe, refers to a meridional oscillation in atmospheric mass (Fig. 7). Positive phases of NAO indicate stronger than average westerlies over the middle latitudes with low-pressure anomalies in the Icelandic region and high-pressure anomalies across the subtropical Atlantic. It is strongly associated with changes in storm activity and northward shift of the Atlantic storm track [Hurrell, 1995; Yan, 2006].
The positive NAO phase shows a stronger than usual subtropical high pressure center and a deeper than normal Icelandic low, while negative NAO phase shows a weak subtropical high and a weak Icelandic low. From August to October, a positive center persists around 5°N–40°N, 20°W–0°E, centered round Azores (Fig. 8). This means the stronger Azores high is associated with more cyclone activity. A very high positive correlation center is observed in middle tropical Atlantic (10°N–20°N, 20°W–40°W) in February and center Australia in April (Figs. 9(a) and 9(b)). Figure 7 shows correlation between the winter NAO index and the winter SLP (averaged over December, January, and February). Figure performed on the site: http://climexp.knmi.nl/ [Oldenborgh et al., 2004] using NCEP-NCAR reanalysis. The location of the Azores and Iceland stations, used to define the NAO index, is indicated.

Those strong correlation zones can then be applied to extract decent predictor time series for North Atlantic hurricane seasonal forecast. Further investigation is needed to explore the physical basis of these correlations.

4. Anomalous SST in the Eastern and Central Tropical Pacific Ocean

Anomalous SST in the eastern and central tropical Pacific Ocean is an indicator of ENSO extreme events. There are various scenarios regarding the ENSO phase and tropical cyclone activity in North Atlantic Basin: fewer and weaker hurricanes occur in El Niño years and more frequent and stronger hurricanes occur in La Niña years [Goldenberg et al., 2001]. Cold phases are observed to have more hurricane
landfalls than neutral years while warm phases see fewer hurricane landfalls [Gray, 1984]. Following Gray, Bove et al. (1998) and Tartaglione et al. (2003) studied the ENSO neutral phase — U.S. hurricane landfall relation and found that the probability of two or more hurricanes making landfall in the United States during ENSO neutral year is about twice as great as that in an El Niño year.

Fig. 9. Correlations between ACE and SLP in (a) February and (b) April.
Since SST in eastern and central tropical Pacific Ocean can change the global meridional and zonal circulation patterns, it does have impacts on North Atlantic hurricane activity. Figures 10(a) and 10(b) illustrate the remote connection between Pacific SSTAs and North Atlantic ACE. A negative center is identified...
in central and eastern equatorial Pacific (ENSO region), which is consistent with above existing studies. However, there is an obvious positive center in western subtropical Pacific (25–35°N, 145–165°E), persistent from May to September. This remote positive correlation is, however, even stronger than the ENSO — ACE relationship, which could be potentially replace the ENSO indices as a more valuable predictor for North Atlantic hurricane seasonal prediction. The mechanism, however, deserves further study.

5. North American Snow Extent

The areal extent of snow cover is thought to influence the atmospheric circulation throughout much of the troposphere by affecting the surface albedo and diabatic heating [Ellis and Hawkins, 2001]. Yan et al. (2010a,b) indicated that the anomalous wintertime snow cover extent and Atlantic hurricane activity are linked through their common association with persistent and hemisphere-wide extratropical circulation anomalies tied to the AO. The low-snow years are usually associated with a positive phase of AO, along with warmer surface temperatures in both North America and Eurasia, while the high-snow years are associated with a negative phase of AO and below-average continental surface temperatures. Figure 11 illustrates that the snow cover significantly correlates with North Atlantic ACE for the period from 1973 to 2005. Figures 12(a) and 12(b) demonstrates how outgoing long-wave radiation (OLR) distributed during high- and low-snow years. The above (below) normal OLR decreases (enhances) the possibility of tropical storm formation and development, and yields substantial variation in hurricane activity in North Atlantic Ocean.

Additionally, normalized North American snow cover extension (million of square feet) and North Atlantic ACE (10^4 kt^2) also demonstrate opposite long-term
trends (Fig. 13), it explains that this inverse snow–hurricane relationship also holds on the decadal time scale.

6. The 500 hPa Geopotential Height (GHT)

The 500 hPa geopotential height (values in meters) represents the height of the 500 hPa pressure surface in the free atmosphere. A deep upper-level trough is presented by the isolines of 500 hPa height. Generally speaking, hurricanes move with the air flow in which they are imbedded. Weaker storms are steered by low-level winds, while the strongest storms move with winds higher up. Hurricanes of low latitude will track to the west, pushed along by the northeasterly trade winds. Hurricanes of higher latitudes track more to the northwest and north steered by anticyclonic flow around the subtropical-high system. Changes in hurricane motion are often linked to extra-tropical circulation. Strong upper tropospheric
troughs extending to low latitude can steer the hurricane northward out of tropics. Figures 14(a) and 14(b) shows a significant correlation zone in tropical Atlantic and north portion of South American continents. This negative correlation zone persists from July to October. It explains that the absence of deep middle-latitude trough allows low-latitude hurricanes to maintain a more westerly path, and enhance the possibility of landfall tropical storms on the eastern seaboard of the United States.

Figure 15 shows the correlation between U.S. total landfall count and 500 mb GHT in September. There are three significant correlation zones (marked in circles). It explains that low GHT off the southwest U.S. coast, high GHT in the east and middle U.S. continental, and high GHT in the east portion of middle North Atlantic are favorable for hurricane to make landfalls on the U.S. Coast.

Correlations between North Atlantic hurricane activity (ACE, U.S. landfalls) and relevant 2D climatic atmospheric and oceanic factors have been investigated. Significant (hurricane-climate atmospheric and oceanic factors) correlation zones were identified. Results reveal that the spatial distribution pattern of climatic/oceanic factors plays a crucial role in the formation, intensification, and track pattern of North Atlantic hurricanes. Correlation analysis is also one of the best ways to extract proper 1D climate atmospheric and oceanic indices for hurricane prediction studies. We next identify, compare, and contrast several years when there was little activity versus those when there was hyper activity.
Fig. 14. Correlations between U.S. ECLFs and 500 hPa GHT (in meters) in (a) August and (b) September.
7. Case Study for Selected Pairs of Years

7.1. Selection of the pairs of years

7.1.1. Pair-1 TC activity — hyperactive year (2005) vs. inactive year (1968)

The ACE index is a wind energy index, defined as the sum of the squares of the maximum sustained surface wind speed (knots) measured every six hours for all named systems while they are at least tropical storm strength. According to NOAA’s ACE definition (Fig. 16), the year 2005 is classified as a hyperactive hurricane season with third most active season on record behind 1950 and 1995 in terms of the ACE index (248.5, 284% of the median (87.5) or 245% of the average (101.3)). The year 2005 is also with record-high 27 tropical storms, 15 hurricanes, and 7 MHs. Of the seven MHs, an unprecedented four of them reached SS Cat-5 status. The season was remarkable for its early beginning and number of storms as well as the intensity of the hurricanes, including the most intense hurricane on record for the Atlantic. In total, seven hurricanes made landfall on the U.S. coastlines, with three strikes on the eastern seaboard, and four on the U.S. portion of the Gulf of Mexico coastline.

The 1968 North Atlantic hurricane season is defined by NOAA as a below-normal hurricane season with the ACE (35) only reaching 39% of the median or 34% of the average. Only eight named tropical storms formed and just four of those reached category-1 hurricane strength, no MH developed. One notable fact
is that there were three tropical storms formed during the month of June making it one of the most active on record, and followed by only one SS Cat-1 hurricane (Dolly) in the normally most active months of August and September. Despite the early season activity, the season ended relatively quietly, showing that early season activity may have little correlation to the rest of the season to follow.

Both 1968 and 2005 fell during very active North Atlantic hurricane eras (1950–1969; 1995–current), and neither of them fell in extreme ENSO years. Statistics for this pair of years are summarized in Table 1.

SSTAs between those two years demonstrate substantial difference during the months from May to August. Spatially, above normal SST is seen in 2005 in the tropical North Atlantic, especially in the MDR and eastern tropical Atlantic near Africa (30°W–10°E, 10°N–20°N), while below normal SST is observed in 1968. In MDR, average SST is 0.72°C above normal in 2005 and −0.61°C below normal in 1968. Near Africa, average SST difference between those two years is 1.43°C. This contrast confirms that other than the MDR, SST in eastern tropical Atlantic near Africa is also a sensitive indicator for North Atlantic hurricane activity.

### Table 1. Pair of years — hyperactive (2005) vs. below-normal (1968).

<table>
<thead>
<tr>
<th>Year</th>
<th>ACE</th>
<th>Tropical storms</th>
<th>Hurricanes</th>
<th>MH</th>
<th>Total U.S. landfalls</th>
<th>Active era</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>248.5</td>
<td>27</td>
<td>15</td>
<td>7</td>
<td>7.0</td>
<td>Yes</td>
</tr>
<tr>
<td>1968</td>
<td>35.0</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>1.0</td>
<td>Yes</td>
</tr>
<tr>
<td>Average (1950–2008)</td>
<td>101.3</td>
<td>11</td>
<td>6</td>
<td>2</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>
The anomalous SST in Pacific Ocean demonstrates substantial difference spatial structures during those two years identified in Sec. 2, the best (Pacific SST and North Atlantic ACE) correlation region is around western subtropical Pacific (25°N–35°N, 145°E–165°E). In this region, however, below and above normal SSTs are observed in 1968 and 2005, respectively.

The difference in sea level pressure fields between 1968 and 2005 is also substantial (Figs. 19(a) and 19(b)). In 1968, above normal SLP occupied the southeast Atlantic (10°W–20°E, 5°S–45°S) and below normal SLP occurred in the Sahel and tropical North Atlantic of the North Africa Coast. This distribution pattern implies a quiet North Atlantic hurricane season. SLP in 2005, however, had an unexpectedly similar distribution pattern as 1968, and this fact reveals that SLP may not have been a significant contributor to the hyperactive 2005 hurricane season.

The vertical shear of the horizontal wind in the MDR is a dominant parameter for tropical cyclogenesis. Figures 20(a), (b) and (c) shows the magnitude of VWS (July–September) in 1968 and 2005, and their differences, respectively. The average of the shear magnitude in the MDR during 2005 is 1.2 m/s, which is less than that of
1968. The strong negative correlation between North Atlantic hurricane formations and VWS explains why more tropical cyclones formed and developed in 2005 than they did in 1968.

7.1.2. Pair-2 U.S. landfalls — six (1985) vs. zero or no (1990) U.S. landfalls

The 1985 Atlantic hurricane season was the first since the 1916 season to have an unusually high number of U.S. landfalls (six hurricanes and two tropical storms) with Hurricanes Danny, Juan, Kate, and Elena making landfall along the northern Gulf Coast, and Hurricanes Gloria and Bob striking the U.S. eastern seaboard. US$4 billion in damage was reported. Though the 1990 hurricane season was as active as that of 1985, it featured relatively weak systems, most of which stayed out to sea. The 1990 season was unusual in that no tropical storms or hurricanes made landfall in the United States, although Tropical Storm Marco weakened to a depression just before making landfall. Records show that this had not happened since the 1890 season.
The 1985 and 1990 Atlantic hurricane seasons are both classified as normal active seasons, and both of them occurred in an inactive hurricane era. However, the difference in the number of U.S. landfall counts was substantial. Detailed statistics are listed in Table 2.

Three distinct differences in SST distribution between 1985 and 1990 are (1) above normal SST observed in the MDR in 1990 and below normal SST in 1985; (2) a warm zone in the western north subtropical Atlantic in 1985 and a cool zone in 1990; (3) a cool zone in east subtropical Atlantic of North Africa in 1985; and (4) a warm zone of North Africa in 1990. Warmer SST is associated with lower SLP, and is more favorable for hurricanes to form and develop.
From Fig. 15, the 500 mb GHT has three significant correlation zones with U.S. landfall counts. Figures 22(a) and 22(b) display the 500 mb GHT in September 1985 and 1990. In 1985, a positive GHT, upper left circle, a negative circle in the lower left, and a positive circle in the upper right, all support a favorable condition for hurricane making landfalls on the U.S. southeast and east coasts. In 1990, however, the GHT in the low left circle is positive, which prevent hurricanes from approaching the U.S. south and east coasts.

7.1.3. Pair-3 U.S. ECLFs — no (1961) vs. three (2004) ECLFs

Despite having only eight total hurricanes, the 1961 hurricane season had seven MHs, the second highest number on record. It is also one of the only four seasons in history to have two or more hurricanes reach SS Cat-5 status. ACE reaches
205 \times 10^4 \text{Kt}^2. One notable occurrence was a lack of activity in that no hurricanes struck the east coast even though five MHs were spawned as African easterly waves that developed over tropical latitudes south of 20°N. Along the Gulf of Mexico coastline of the U.S., however, a Caribbean-origin SS Cat-5 hurricane named Carla struck Texas, killing 49 and causing US$325 million in damage.

The 2004 season had 15 named tropical storms, 9 hurricanes, and 6 MHs. The ACE of 225, ranked 2004 it was the fourth most active season since 1950. The season was notable as one of the deadliest and most costly Atlantic hurricane seasons on record. Five named storms, Bonnie, Charley, Frances, Ivan, and Jeanne, made landfall in the single state of Florida; three of them with at least 115 mph (185 km/h) sustained winds. This is the only time in recorded history that four hurricanes affected Florida in one year. Floodwaters in many southeastern U.S. regions were at record levels.

According to NOAA’s definition of North Atlantic hurricane season types, the 1961 and 2004 hurricane seasons are both categorized as hyperactive hurricane season, with ACEs exceeding 175% of the median (87.5). Table 3 lists the statistics.
Table 3. Pair of years — no (1961) vs. three (2004) ECLFs.

<table>
<thead>
<tr>
<th>Year</th>
<th>ACE storms</th>
<th>Hurricanes</th>
<th>MH landfalls</th>
<th>East coast landfalls</th>
<th>Gulf coast landfalls</th>
<th>Active era</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>205</td>
<td>11</td>
<td>8</td>
<td>7</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2004</td>
<td>225</td>
<td>16</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Anomalous SST in the SSTA–ECLF correlation zone (35°W–5°E, 35°N–60°N) in 1961 (Fig. 23(a)) was negative in contrast to being positive in 2004 (Fig. 23(b)). The 200 mb wind in 1961 displays weaker westward component and stronger northerly component than those in 2004. Therefore, hurricanes in 2004 traversed longer westerly tracks than in 1961. Figures 24(a) and 24(b) compares the SSTAs in January–February in 1961 to those of 2004. The correlation zone is negative in 1961 and positive in 2004. This finding confirms that SSTA in this correlation zone is a sensitive indicator/predictor for ECLF occurrences.

Figures 25(a) and 25(b) displays the 500 mb geopotential height in September 1961 and 2004, respectively. The below-normal (1961) and above-normal (2004) GHTs in circled correlation zones implied a quiet landfall hurricane season for 1961 and an active landfall season for 2004.
Fig. 23. Anomalous SST and 200 mb Wind in (a) September, 1961 and (b) September 2004.
8. Principal Component Analysis among Climate Factors, North Atlantic Hurricane Activity and the Hurricane Track Density Function

The principal component analysis (PCA) technique employs empirical orthogonal functions (EOFs) in keeping with Lorenz (1956). In particular, here we employ singular value decomposition (SVD) to compute the EOFs, which greatly simplifies computational requirements [Kelly, 1988]. This methodology has been widely used in meteorological and oceanic data analysis [Rasmusson et al., 1981; Anderson and Gyakum, 1989; Knappenburger and Michaels, 1993; Lee and Cornillon, 1995]. EOF analysis determines a set of orthogonal functions that characterizes the co-variability of the time series. The advantage of EOF analysis is that it provides a compact description of the spatial and temporal variability of data series in terms of orthogonal functions or statistical “modes.” Analysis of these EOF modes could provide physical insight into the data that will be useful in identifying the principal factors that influence hurricane intensity and track patterns.
8.1. EOF analysis on Atlantic SST and its dominant modes associated with North Atlantic tropical cyclone activity

The computation of EOFs was carried out with monthly SST resolution on the $2.5^\circ \times 2.5^\circ$ grid using an iterative singular decomposition technique where a first guess field is repeatedly projected through the dataset in time and then space until convergence is reached. After an EOF has been found, the corresponding variance is removed and the process is repeated to find the next most important EOF. Figure 26 displays spatial structures of the first three dominate EOF modes of North Atlantic SSTAs in May and June. They explain 57.09%, 13.52%, and 6.03% of the total variance, respectively.

Conducting Monte Carlo experiments is one reliable way to assess the statistical significance of EOFs. One approach is to randomly assign scrambling starting data...
for each of the SST in the dataset and comparing the residual variances of the dominant EOFs with their counterparts as it was done in Anderson and Gyakum (1989). Our experiment is designed to randomly generate subsets of the original dataset (subset sizes > one forth of the original size), and comparing the EOFs for different subsets against the ones for the full dataset using spatial correlation coefficients. Results indicated that the first three EOFs retained their rank in the hierarchy and exhibited substantial levels of similarity — 93 of the 100 Monte Carlo control runs matched their counterparts with a spatial correlation coefficient of at least 0.78, representing a substantial statistical significance of the first three leading EOFs.
In order to interpret the physical meanings of the EOFs and their spatial and temporal variability, it is important to check if any of the EOFs does not represent the physical fields. One approach for simplifying the interpretation of EOF analysis is the technique of factor rotation, which has been widely used in meteorological applications [Richman and Lamb, 1985]. In this study, the rotated EOFs are computed by using the VARIMAX program [Cureton and D’Agostino, 1983]. When an EOF rotation is carried out, one needs to choose the truncation point, M, for the description of the field by using the first M order EOF components.

Our experiment shows that the first three rotated EOFs explain a similar amount of variance as those explained by the first four or five EOFs involved in the rotation. Additionally, the space and time structures of the first three rotated EOFs are nearly identical to the cases where M takes 4 or 5. Thus, M = 3 is a reasonable truncation point. The temporal distributions of the top three EOFs and the rotated EOFs of Atlantic SSTAs are also nearly identical, which further shows the reliability of the first three leading EOFs.

The spatial distribution of EOF1 (Fig. 26(a)) is characterized by a single high positive value over the study domain. A large positive weight represents an above-normal SST in the region, and a negative weight indicates a below-normal SST. The spatial pattern of EOF2 (Fig. 26(b)) shows a tripole structure in that its values are positive in the middle Atlantic region (20°N–40°N), negative in the lower tropics (<20°N), and in the upper region of the study domain (>40°N). This depicts a meridional gradient of the SST. The spatial pattern of EOF3 is shown in Fig. 26(c). It shows a positive center in the middle-west Atlantic near the U.S. east coast coupled with positive values in the central-eastern Atlantic near West Africa.

![The dominant three EOF Modes of SSTAs (May-Jun)](image-url)
In general, the value of EOF3 increases from west to east, indicating a west–east gradient of the SST.

Relationships between the dominant SST EOF and ACE are now calculated. The first and third EOF components and ACE are positively correlated at above 99% (R = 0.5856) and 95% (R = 0.3034) confidence level (CFL), respectively. This fact implies that the above-normal SST in the whole North Atlantic Basin (positive phase of EOF1) is favorable for hurricane formation and development. The third EOF mode explains that the above-normal SST in the east portion of the NA of the West African coast provides a favorable condition for ACE increase. However, ACE has no connection to the second EOF mode, which means the second SST mode explains something other than Modes 1 and 3.

The first EOF mode is also strongly correlated with overall U.S. landfall count (R = 0.3258) and U.S. ECLF counts (R = 0.3921) at above 95% CFL (Table 4). Other EOF modes have no significant relationships with either U.S. landfalls in general or U.S. ECLFs in particular.

The North Atlantic hurricane track density function (HTDF) is the description of both hurricane track and hurricane frequency accomplished by evaluating a summation of all daily hurricane tracks in the dataset on a 2 × 2 grid, as defined by Yan (2006). The first three dominant EOF modes of HTDF represent the overall basin-wide hurricane frequency, the E–W and N–S track movements, and account for 30.47%, 12.89%, and 9.72% of the variance, respectively. The correlations among the dominant EOFs of HTDF and SST are then calculated (Table 4).

The first SST EOF mode has a significant correlation with all the three HTDF EOFs, and this implies the SST EOF1 not only relates to hurricane frequency, but the hurricane track as well, it is, therefore, strongly associated with both overall NA hurricane activity (ACE) and U.S. (U.S. east coast) landfall frequency. SST Mode 3 correlates with HTDF1 and HTDF2 at 90% CFL; SST Mode 2 has no connection with any of the HTDF modes, and has nothing to do with hurricane activity.

The goal of EOF analysis was to determine if there is any statistical connection between NA tropical cyclone and hurricane activity and SSTA fields. By using the EOF procedure, we are able to present the primary modes of variability for both fields in the most compact form possible, which is the real advantage of the EOF procedure. In terms of the hurricane track and SSTA fields, we found that there

<table>
<thead>
<tr>
<th>R</th>
<th>HTDF1</th>
<th>HTDF2</th>
<th>HTDF3</th>
<th>ACE</th>
<th>U.S. landfall</th>
<th>EC landfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST Mode 1</td>
<td>0.5121</td>
<td>0.4047</td>
<td>-0.3282</td>
<td>0.5856</td>
<td>0.3258</td>
<td>0.3921</td>
</tr>
<tr>
<td>SST Mode 2</td>
<td>0.1535</td>
<td>0.0092</td>
<td>-0.0938</td>
<td>-0.096</td>
<td>0.0011</td>
<td>0.1442</td>
</tr>
<tr>
<td>SST Mode 3</td>
<td>0.2474</td>
<td>0.2381</td>
<td>-0.0849</td>
<td>0.3034</td>
<td>0.2305</td>
<td>0.2024</td>
</tr>
<tr>
<td>ACE</td>
<td>0.8298</td>
<td>0.2261</td>
<td>-0.6145</td>
<td>1.0000</td>
<td>0.5975</td>
<td>0.4873</td>
</tr>
<tr>
<td>U.S. Landfall</td>
<td>0.3877</td>
<td>0.4419</td>
<td>-0.5812</td>
<td>0.5975</td>
<td>1.0000</td>
<td>0.7628</td>
</tr>
<tr>
<td>EC Landfall</td>
<td>0.4893</td>
<td>0.4572</td>
<td>-0.4641</td>
<td>0.4873</td>
<td>0.7628</td>
<td>1.0000</td>
</tr>
</tbody>
</table>
were connections between the variables. First, NA hurricane activity (frequency and landfalls) could be predicted from earlier SSTA fields, as the SSTA fields we used here are May–June, one month ahead of the active hurricane season. We also can conclude that it is possible to specify the NA hurricane activity (ACE and landfalls) based on the coincident SSTA field. Those conclusions would have been difficult to arrive without using EOF procedure.

9. 2010 North Atlantic Hurricane Forecast (April)

9.1. Background

Yan (2006) and Yan et al. (2006) presented a new methodology for selecting factors to predict the overall North Atlantic hurricane activity and the number of hurricanes (NHs) that make landfall along the Atlantic eastern seaboard of the U.S. and the U.S. coastline of the Gulf of Mexico. Recent analysis on 2D climate atmospheric and oceanic data and their correlation with North Atlantic hurricane activity also provides a way to identify hurricane-related climate factors [Yan and Pietrafesa, 2010]. A mathematical model applied with this methodology was tested and showed excellent prediction skills. It also demonstrates excellent hind-casting skills for the past 60 years (1950–2009). For year 2010, our forecast covers (1) overall hurricane activity in the entire North Atlantic Basin; (2) landfall hurricane activity from Texas to Maine; and (3) landfall counts along U.S. coastlines including the eastern seaboard and the Gulf of Mexico. Our forecasting scheme assumes that oceanic and atmosphere behaviors could be viewed as a Stable Process, i.e. the atmosphere would continue to behave in the future as it has in the past. Prediction is, therefore, possible based on pre-existing climatic conditions. We note here that we are predicting “tropical cyclones” and hurricanes using the well-known Saffir/Simpson scale.

9.2. Prediction categories

The following variables are predicted: (1) North Atlantic ACE; (2) the total number of named tropical storms (TS); (3) the NHs to form in the entire North Atlantic Basin (including the Gulf of Mexico and the Caribbean Sea); (4) the number of MHs according to the Saffir-Simpson Category Scales 3, 4, 5; (5) the number of land-falling hurricanes along the U.S. eastern Atlantic seaboard (ECLF); and (6) the number of land-falling hurricanes along U.S. coastline of the Gulf of Mexico (GMLF).

A new methodology was applied here for landfall prediction [Yan et al., 2009], which is based on the North Atlantic hurricane season type classification. According to statistics of the records of North Atlantic ACE and hurricane activity in the past few decades (1950–2009), landfall hurricane frequency on the eastern Seaboard of the U.S. is closely associated with the weather patterns that are linked to overall hurricane activity in the North Atlantic.
9.3. Model and predictors

A number of statistical prediction models were developed with the application of statistical software (SAS) generalized linear model (GENMOD) that fits a generalized linear model to the data via a maximum likelihood estimation of the response variable. The distribution of response variables (e.g. landfall hurricane count) is specified as Poisson, and the link function is chosen to be logarithmic. It estimates the parameters of the model numerically through an iterative process.

PCA of the North Atlantic (NA) HTDF yields three dominant EOF modes [Yan, 2006]. The first EOF mode represents the overall NA hurricane activity; the second and third modes demonstrate dipole structures, which are associated with hurricane track accumulation in the east–west (E–W) and north–south (N–S) directions, respectively. Analysis of correlations between those EOF modes and climatic atmospheric and oceanic factors [Yan, (2006); Yan et al., (2006)] determined the principal predictors associated with various predicting variables.

The Atlantic multidecadal oscillation (AMO) represents a cycle in the large-scale atmospheric flow and ocean currents in the North Atlantic Ocean that combine to alternately increase and decrease Atlantic SSTs. It is defined as the mean SST between 75°W and 7.5°W and south of 60°N. The AMO is thought to strongly influence the incidence of intense hurricanes [Mann and Emanuel, (2006); Sriver and Huber, (2006)]. They show that the average intense hurricane count during the warm phase of the AMO years is more than double of the count during the cool phase years. Our study notices that, the AMO also demonstrates strong positive correlations with the number of landfall strikes along the east coast of the United States, which changes dramatically between cool and warm AMO periods. For example, an average of 1.10 hurricanes per year has landed on the U.S. eastern seaboard during the current warm phase (1995–2009) of the AMO, while only 0.36 hurricanes/year made landfalls during the last cool phase (1970–1994) of the AMO. AMO indices from January to March are applied in our prediction models.

The tropical Atlantic dipole mode is characterized by mean SSTA differences between the tropical NA and the tropical South Atlantic as proposed by Sutton et al. (2000). In Yan (2006), the dipole mode of the tropical Atlantic SSTA has shown to be strongly correlated with all of the three dominant HTDF EOF modes. Therefore, the DM is not only associated with overall North Atlantic hurricane activity, but also associated with hurricane track patterns. The influence of the DM on U.S. eastern seaboard landfalls has already been discussed in Yan (2006). He suggested that the DM, coupling the tropical and subtropical atmospheric circulation, controls the steering of hurricanes. The DM indices are chosen as a predictor in our model system.

The tropical South Atlantic (TSA) SST index is the anomaly of the average of the monthly SST across the domain of the Equator-20S and 10E–30W, which was identified by Goedenberg and Shapiro (1996), as having the largest sensitivity to changes in vertical shear. This index demonstrates a strong positive correlation
with the NHs that pass west of 75°W. The warmer SST in the tropical South Atlantic Ocean enhances low-level vorticity and convergence, and consequently lowers sea-level pressure, and reduces vertical shear in the trade wind zone. The above normal conditions in this area are favorable for hurricanes to be developed.

As shown above, the spatial distribution of SST in the Atlantic Basin plays a crucial role in tropical cyclone formation and development. Based on the 60 year (1950–2009) historical data archive, correlations between hurricane predicted categories (ACE, TS, NH, MH, ECLF, and GMLF) and the 2D SST in the Atlantic Basin are now analyzed (Figs. 28(a)–28(f)). In each case, the best significant correlation center is identified (circled). The anomalous SST time series is, therefore, extracted from those correlation domains and applied as a predictor for each category.

For the prediction of the ACE, the anomalous SST time series is taken at longitude from 4°W to 22°W, latitude from 24°N to 42°N; for TS & NH, longitude from 22°W to 48°W, latitude from 0°N to 16°N; For MH, longitude from 24°W to 50°W, latitude from 0°N to 18°N; for ECLF, longitude from 24°W to 40°W, latitude from 18°S to 40°S; for GMLF, longitude from 36°W to 0°E, latitude from 2°S to 18°S. All of these time series show best sensitivity to associated prediction categories (Fig. 29).

It is well accepted that hurricane activity in the North Atlantic basin is affected by ENSO through changes in the Atlantic atmospheric circulation, largely through the VWS. Hurricane activity is suppressed when an El-Niño event occurs and is
Fig. 28. (Continued)
Fig. 28. (Continued)
enhanced when a La-Niña event prevails [Gray (1984); Shapiro (1987)]. Gray (1984) has also shown a three-to-one ratio in continental U.S. land-falling intense hurricanes, with 0.74 per year striking during non-El-Niño years and only 0.25 per year during El-Niño events. Recently, Bove et al. (1998) analyzed all continental U.S. land-falling hurricanes and intense hurricanes of this century by the concurrent phase of ENSO. They found that the probability of at least two hurricanes striking
the United States is 28% during El-Niño years compared with 48% during neutral years and 66% during La-Niña years. Previous 60-year analysis identified mean ENSO index from September to October demonstrates a significant negative correlation with North Atlantic ACE (R = −0.35, p < 0.011), and the May–June mean indices is strongly associated with the number of land-falling hurricanes along the U.S. east coast. Figure 30 summaries the ENSO forecast outputs from different sources.

Another predictor is the average NAO index over the period from May to June. Historically, the NAO displays a strong negative association with the number of U.S. eastern seaboard landfall strikes. The below-normal NAO index from January to February suggests an above-normal landfall season. The NAO is associated with a subtropical high pressure cell displaced further west and south from its mean position [Elsner et al., 2000], which implies that more hurricane tracks will accumulate in the western portion of the North Atlantic Ocean and so hurricanes are more likely to propagate further westward toward the U.S. eastern seaboard.

An inverse relationship has been recently identified between the North American snow extent and North Atlantic tropical cyclone activity [Yan et al., 2009].
The anomalous wintertime snow cover extent and Atlantic hurricane activity are linked through their common association with persistent and hemisphere-wide extratropical circulation anomalies tied to the AO. Additionally, normalized North American snow cover extension (million of square feet) and North Atlantic ACE also demonstrate opposite long-term trends.

All those selected predictors demonstrate significant correlation with one or more prediction variables listed in Sec. 9.4. The objective statistical bootstrap techniques show that predictors having statistically significant correlation with predicting variable over long dataset period could add credibility to the forecast scheme.

9.4. Our model April 2010 forecast for the 2010 hurricane season

Table 5 lists the predictors applied in our April 2010 forecasting scheme.

Table 5. The list of April 2010 predictors for year 2010 tropical cyclone activity.

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Anomalies for April 2010 forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Atlantic multidecadal oscillation (AMO) (January–March)</td>
<td>+0.5919</td>
</tr>
<tr>
<td>(b) Tropical Atlantic dipole mode (DM) (February–March)</td>
<td>+0.5489</td>
</tr>
<tr>
<td>(c) North tropical Atlantic SSTAs (TSA) (January–February)</td>
<td>+1.0000</td>
</tr>
<tr>
<td>(d) SSTA selected for ACE prediction</td>
<td>+0.5139</td>
</tr>
<tr>
<td>(e) JMA El-Niño-South Oscillation index (ENSO) (September–October)</td>
<td>−0.1144</td>
</tr>
<tr>
<td>(f) North American snow extent (NASE) (January)</td>
<td>+0.0020</td>
</tr>
</tbody>
</table>

Note: "NASE is not applied in this 2010 prediction scheme. A plus (+) means that positive values of the parameter indicate increased tropical cyclone and hurricane activity in 2010, and a minus (−) means that positive values of the parameter indicate decreased tropical cyclone and hurricane activity in 2010.

Table 6. Analog years for 2010 with predictors and associated predicted category.

<table>
<thead>
<tr>
<th>Year</th>
<th>ACE</th>
<th>TS</th>
<th>NH</th>
<th>MH</th>
<th>AMO</th>
<th>ENSO</th>
<th>DM</th>
<th>SSTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>199</td>
<td>12</td>
<td>9</td>
<td>6</td>
<td>0.2286</td>
<td>−0.5827</td>
<td>0.1696</td>
<td>0.2499</td>
</tr>
<tr>
<td>1958</td>
<td>121</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>0.5902</td>
<td>−0.0821</td>
<td>0.6981</td>
<td>−0.1442</td>
</tr>
<tr>
<td>1998</td>
<td>182</td>
<td>14</td>
<td>10</td>
<td>3</td>
<td>0.7702</td>
<td>−0.2436</td>
<td>0.1047</td>
<td>0.9934</td>
</tr>
<tr>
<td>2004</td>
<td>225</td>
<td>15</td>
<td>9</td>
<td>6</td>
<td>0.6375</td>
<td>−0.1279</td>
<td>0.4441</td>
<td>0.9275</td>
</tr>
<tr>
<td>2005</td>
<td>248</td>
<td>28</td>
<td>15</td>
<td>7</td>
<td>0.5944</td>
<td>−0.0498</td>
<td>0.3297</td>
<td>0.0143</td>
</tr>
<tr>
<td>2007</td>
<td>74</td>
<td>15</td>
<td>8</td>
<td>2</td>
<td>0.5877</td>
<td>−0.3243</td>
<td>0.3917</td>
<td>0.7131</td>
</tr>
<tr>
<td>2010</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5919</td>
<td>−0.1144</td>
<td>0.5489</td>
<td>0.5139</td>
</tr>
<tr>
<td>Average</td>
<td>103</td>
<td>10.8</td>
<td>6.2</td>
<td>2.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note: In the following, prediction schemes for the listed category in Sec. 9.4 are analyzed.
9.4.1. **North Atlantic ACE**

The ACE is a measure of total North Atlantic tropical cyclone activity. It is defined as the sum of the squares of the maximum sustained surface wind speed (knots) measured every six hours for all named systems while they are at least of tropical storm strength [Bell et al., 2000]. The 60-year (1950–2009) long-term mean ACE is 101 (10^4 kt^2). From available predictors in 2010, each of those predictors calls for 2010 to be a busy hurricane season.

Model estimation of this year’s ACE is 160, which is 158% of the long-term average. The upper and lower bounds of model estimation within 70% confidence level (CFL) are: [157 164]. According to NOAA’s season type definition, the 2010 hurricane season is projected to be a hyperactive season type.

9.4.2. **The NHs and tropical storms (TS) to form across the entire North Atlantic Basin, including the Gulf of Mexico and the Caribbean Sea**

Over the past 60 years (1950–2009), TS ranges from 4 (1983) to 28 (2005). For the year 2010, model predicted theoretical value for this category is 15.9, which is 147.6% of the 60-year average (10.8). The range of TS number at 70% confidence level is 14–17.

9.4.3. **The NHs predicted to form in North Atlantic Basin, including the Gulf of Mexico and the Caribbean Sea**

Hurricanes that have developed in North Atlantic Basin varied in a large range during the past few decades. There were only two formed in 1982; however, fifteen formed in 2005, which set a record high. The average hurricane number from 1950 to 2009 is 6.2. With the same predictors applied in Table 2, our model estimation for this variable in the year 2010 is 8.99, which is 145% of the climatology (6.2). The predicted number range of hurricanes associated with the largest and second largest probability is 8–9. The hurricane number range at 70% CFL is 7–9. A probability forecast is given in Table 7.

9.4.4. **Number of MHs predicted to form in the North Atlantic Basin, including the Gulf of Mexico and the Caribbean Sea**

The annual number of MHs in North Atlantic Basin has ranged from 0 to 8, with 2.7 on average. The theoretical estimation from the model is 4.99, which is 181% of the average. The upper and lower bounds of model estimation at the 70% confidence level are 4–6. The probability forecast is given in Table 8.

<table>
<thead>
<tr>
<th>Number</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability (%)</td>
<td>1.5</td>
<td>3.4</td>
<td>6.1</td>
<td>9.1</td>
<td>11.9</td>
<td>13.2</td>
<td>13.2</td>
<td>11.8</td>
<td>9.7</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Table 8. Probabilities associated with estimated MH number in 2010.

<table>
<thead>
<tr>
<th>Number</th>
<th>Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>8.5</td>
</tr>
<tr>
<td>3</td>
<td>14.1</td>
</tr>
<tr>
<td>4</td>
<td>17.6</td>
</tr>
<tr>
<td>5</td>
<td>17.6</td>
</tr>
<tr>
<td>6</td>
<td>14.6</td>
</tr>
<tr>
<td>7</td>
<td>10.4</td>
</tr>
<tr>
<td>8</td>
<td>6.5</td>
</tr>
</tbody>
</table>

9.4.5. Hurricanes predicted to make landfall along the eastern seaboard of the United States

Landfall prediction largely depends on the prediction of the North Atlantic hurricane season type. Though predicted ACE \((160 \times 10^4 \text{kt}^2)\) for the 2010 hurricane season falls into a hyperactive season type (defined as \(ACE > 153 \times 10^4 \text{kt}^2\)), it is on the edge of the lower bound of hyperactive and upper bound of above-normal; therefore, the 2010 season may also fall into the above-normal type. Here our landfall prediction model for both hyperactive and above-normal season types is applied.


Predictors applied in this forecasting scheme were AMO, ENSO, ACE and anomalous SST in our selected domain (Fig. 28(e)) as shown in Fig. 31.

There were four years in history with similar predictor combination like 2010 (Table 9), and during all of those years, the landfall hurricane counts fell into the range 0–1.
Table 9. Analog years for 2010 with predictors and associated landfall events listed.

<table>
<thead>
<tr>
<th>Year</th>
<th>Landfalls</th>
<th>AMO (January)</th>
<th>ENSO (May–June)</th>
<th>ACE</th>
<th>SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>0</td>
<td>0.1719</td>
<td>−0.7319</td>
<td>0.0068</td>
<td>0.3654</td>
</tr>
<tr>
<td>1999</td>
<td>1</td>
<td>0.6345</td>
<td>−0.2469</td>
<td>0.5137</td>
<td>0.2406</td>
</tr>
<tr>
<td>2003</td>
<td>1</td>
<td>0.2638</td>
<td>−0.2469</td>
<td>0.5000</td>
<td>0.5018</td>
</tr>
<tr>
<td>2008</td>
<td>0</td>
<td>0.3809</td>
<td>0.1443</td>
<td>0.2876</td>
<td>0.1227</td>
</tr>
<tr>
<td>2010</td>
<td>?</td>
<td>0.3781</td>
<td>−0.0269</td>
<td>0.3116</td>
<td>0.7312</td>
</tr>
</tbody>
</table>

The Atlantic multi-decadal oscillation (AMO) has maintained a positive phase since 1995 (Fig. 31). The positive AMO phase in 2010 (January) suggests favorable ocean condition that could enhance the overall North Atlantic hurricane activity and subsequently increase the possibility and frequency of landfall events along the U.S. eastern seaboard.

The mean ENSO index (May–June) used in this scheme was derived from the JMA forecast model, which results in a value of −0.0269. Most of the ENSO prediction models suggested a neutral or negative ENSO condition for the next few months. Since ENSO index is one of the most sensitive predictors in the model and it depends on prediction, this value should be updated in the forecast as long as new prediction and or observations are available.

The extracted anomalous SST time series shows negative correlation with ECLF (Fig. 29) and the positive value of SSTA in 2010 in selected domain suggests an inactive ECLF landfall season. Figure 32 shows the comparison between observations and the hind-casting output from the prediction model.

The model shows excellent skill (root mean square error score is 32.6% above climatology). The model yields an estimated intensity = 0.58, the lower and upper bounds at 70% confidence level is: [0.34, 1.01]. Since the 60-year (1950–2009) ECLF average is 0.64/year, we, therefore, estimate the 2010 U.S. ECLF activity is 90.6% of the long-term average. This percentage was computed via: the estimated intensity (0.58)/average landfall hurricane number per year (0.64)*100. The most likely range is therefore [0 1].

![Fig. 32]
Table 10. Landfall probability associated with U.S. eastern seaboard landfall counts.

<table>
<thead>
<tr>
<th>Number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probabilities (%)</td>
<td>56.0</td>
<td>32.5</td>
<td>9.4</td>
<td>1.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Climatology (%)</td>
<td>55.0</td>
<td>30.0</td>
<td>10.0</td>
<td>5.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Following a Poisson distribution, a probability forecast is proposed, the maximum probability, 56.0%, is associated with zero landfall (where the long-term, 1950–2009, mean of one event is 55.0%). Probability associated with one landfall number is 32.5% (mean: 30.0%). Probability of two landfalls is 9.4% (mean: 10.0%). The estimated probability: for at least one hurricane making landfall is 44% (mean: 45%); at least two landfalls is 11.5% (mean: 15.0%) (Table 10).

Based on analog analysis of the past 60-year (1950–2009) model hind-cast output and observation, we conclude that the most likely range of landfall strikes on the East Coast of the U.S. in 2010 is 0–1. The number of landfall strikes with maximum probability is 0.

10. Hurricanes Predicted to Make Land Fall along the U.S. Portion of the Gulf of Mexico (GMLF)

Many predictors necessary for this predicting category are generally not available until June or early July. Predictors available so far for our April 2010 forecast of 2010 were: the Tropical South Atlantic (TSA) index, ACE and SSTAs extracted from elected domain (Fig. 28(f)). TSA is the anomaly of the average of the monthly SST from Eq-20\(^\circ\)S and 10\(^\circ\)E–30\(^\circ\)W, its normalized value in 2010 is +1.0, suggests a very active landfall season; however, anomalous SST selected domain in 2010 is positive (0.4632), which implies an inactive landfall season. Model estimated value is 1.70. Long-term (1950–2009) mean number of landfalls is 0.98. Therefore, we expect GMLF in 2010 season is 173% of the 60-year average. Table 11 shows the forecasted landfall probabilities associated with landfall numbers this year.

Table 11. Landfall probability associated with Gulf of Mexico landfall counts.

<table>
<thead>
<tr>
<th>Number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probabilities (%)</td>
<td>18.3</td>
<td>31.1</td>
<td>26.4</td>
<td>15.0</td>
<td>6.4</td>
<td>2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Climatology (%)</td>
<td>35.0</td>
<td>41.7</td>
<td>18.3</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note: From analog analysis, the most likely number range of landfall in 2010 is 1–2.

11. Summary of Our April 18 2010 Forecast

Data acquired so far signals an above-normal 2010 hurricane season in the North Atlantic Basin. ACE is expected to be 160, which is 158% of the 60-year long-term
Table 12. 2010 Atlantic basin seasonal hurricane forecast.

<table>
<thead>
<tr>
<th>Category</th>
<th>Forecast value</th>
<th>Forecast range</th>
<th>Climatology</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>160</td>
<td>[157–164]</td>
<td>101</td>
</tr>
<tr>
<td>TS</td>
<td>16</td>
<td>[14–17]</td>
<td>10.8</td>
</tr>
<tr>
<td>NH</td>
<td>8</td>
<td>[7–9]</td>
<td>6.2</td>
</tr>
<tr>
<td>MH</td>
<td>5</td>
<td>[4–6]</td>
<td>2.7</td>
</tr>
<tr>
<td>ECLF</td>
<td>0</td>
<td>[0–1]</td>
<td>0.64</td>
</tr>
<tr>
<td>GMLF</td>
<td>1</td>
<td>[1–2]</td>
<td>0.98</td>
</tr>
</tbody>
</table>

The implications of the forecast created in April 2010 for the 2010 hurricane season, if it carried a high level of certitude, are likely significant to emergency planners, the insurance industry and the public. The probability of a high level of overall tropical storm activity with few landfalls creates entirely different mitigation strategies for an upcoming season than do other scenarios such as seasons with: high levels of TC activity with many probable landfalls, low levels of TC activity with most making landfalls and low levels of TC activity with few or no landfalls. It is for the social scientist community to provide that perspective. Physical and mathematical scientists do not generally possess that skill set. However, we believe that the prior information may have great value.

12. Updates of Our Model Forecasts, the Actual Season and Conclusions

At the time of publication of this manuscript, the North Atlantic Ocean Basin Tropical Cyclone/Hurricane Season is winding down. Updates of our forecasts are provided in Table 13. Also provided in Table 13 is what has actually occurred as of 10/31/2010. To date, most of the forecasted categories are well positioned relative to the prediction range (70% confidence level), as shown. Our initial forecast was issued on April 18, updated on June 15 and again on August 18. Many prediction categories were adjusted, and showed more accuracy after updating. What has astounded the tropical cyclone community is the fact that the North Atlantic TC
and hurricane season has been very busy, yet no direct land falls of event eyes have occurred onto US states; except for Hurricane Alex (25 June to 02 July) which made landfall along the Gulf Coast along the far eastern border of Mexico, very close to the western border of Texas.

It is of note that since 1900 there is no precedent of an Atlantic hurricane season with 10 or more hurricanes where none has struck the United States as a hurricane. Our forecast of 16–18 named events is one short of the total number of 19 and our forecast of 9–11 hurricanes is also one short of what has occurred to date. However, our forecast of 4–6 MHs is spot on as five have occurred. Our forecast of 0 (zero) hurricane land falls along the eastern seaboard of the United States and of one onto a U.S. state in the Gulf of Mexico are both remarkable, given that no hurricanes have made land fall along either U.S. coastline, especially considering the close encounter of Texas with Hurricane Alex.

In summary, our study has shown that the connection between the condition and phases of many 2D climate factor months in advance of an upcoming tropical cyclone/hurricane season is very powerful in determining the frequency of occurrence of types of events including named events, hurricanes, and MHs. Moreover, the states of these climate factors several months in advance of the onset of a season may well determine the ultimate pathways of the hurricanes. We predicted the 2010 season to be anomalous in that while the total numbers of hurricanes predicted and that have occurred is well above normal; however, the number of land falls, zero to date, is singular in recorded history. These remarkable results imply that the use of empirical modal decomposition [Huang et al., 1998], ensemble empirical modal decomposition [Wu and Huang, 2009], and multi-dimensional ensemble empirical decomposition [Wu et al., 2009], which has the power to decompose climate factors both temporally and spatially, may pioneer a new era in tropical cyclone forecasting. The mathematical and statistical methodologies used in this study, which could be coupled to next generation “empirical modal decomposition,” suggest that this may signal a new era in the future of tropical cyclone forecasting, including the reliable prognostication of numbers of events, intensities of events, and the pathways of those events. The ability to reliably predict the probability and location of land falls of these destructive events would be very powerful indeed.

### Table 13

<table>
<thead>
<tr>
<th>Category</th>
<th>April</th>
<th>June</th>
<th>August</th>
<th>As of Oct. 31</th>
<th>Climatology</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECLF</td>
<td>0 [0–1]</td>
<td>0 [0–1]</td>
<td>0</td>
<td>0</td>
<td>0.64</td>
</tr>
<tr>
<td>GMLF</td>
<td>1 [1–2]</td>
<td>2 [1–3]</td>
<td>1 [1–2]</td>
<td>0</td>
<td>0.98</td>
</tr>
</tbody>
</table>

*Note: *Within 70% Confidence Level.
Acknowledgments

The authors gratefully acknowledge the support of both the National Oceanic & Atmospheric Administration, National Climatic Data Center, and to the Defense Advanced Research Projects Agency, for funding this study. Jim Epps is acknowledged for his efforts to capture the many data sets from the various federal agency archives, running the considerable number of algorithms, and in producing the plots and figures. N. E. Huang and Z. Wu were supported by a grant from Federal Highway Administration, DTFH61-08-00028, and the grants NSC 98-2627-B-008-004 (Biology) and NSC 98-2611-M-008-004 (Geophysical) from the National Science Council, and finally a grant from NCU 965941 that has made the conclusion of this study possible. N. E. Huang is also supported by a K. T. Lee endowed Chair at NCU. ZW was also sponsored by the NSF of USA grant ATM-0917743.

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