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Forecasting October–November Caribbean hurricane days

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[1] October–November Caribbean hurricane activity can have profound impacts on the region through loss of life and devastation of property. Large-scale climate parameters associated with active late seasons in the Caribbean are investigated in this paper. Among the primary features that are noted are atmospheric and oceanic conditions typical of La Niña and a larger-than-normal Atlantic Warm Pool as well as reduced trade wind strength in the western tropical Atlantic. A two-predictor statistical model has been developed to forecast the number of hurricane days in the Caribbean during October–November. The first predictor is the July–September–averaged Nino 3.4 index, a measure of El Niño-Southern Oscillation, while the second predictor measures July–September–averaged sea surface temperatures in the western part of the tropical Atlantic extending into the Caribbean, which very closely correlates with the size of the Atlantic Warm Pool. These two predictors can hindcast approximately 58% of the variance in the number of October–November Caribbean hurricane days over the period from 1982 to 2010 when a drop-one cross validation procedure is applied. The predictors also correlate significantly with physical features in the Caribbean basin that are known to impact tropical cyclones. While these strong correlations between predictors and physical features extend back to an independent period from 1900 to 1981, the correlations between individual predictors and October–November hurricane days degrade considerably during the earlier period.

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1. Introduction

[2] Tropical cyclone (TC) activity in the Caribbean during the months of October and November can devastate the region and surrounding areas (e.g., Hurricane Mitch in 1998, Hurricane Wilma in 2005). Mitch (1998) was responsible for over 9000 deaths in Central America (J. L. Guiney and M. B. Lawrence, Preliminary report of Hurricane Mitch, 1999, http://www.nhc.noaa.gov/1998mitch.html), while Wilma (2005) developed in the western Caribbean and then severely impacted the state of Florida, causing over 10 billion dollars in insured damage (R. J. Pasch et al., Tropical Cyclone Report: Hurricane Wilma, unpublished report, 27 pp., 2006, http://www.nhc.noaa.gov/pdf/TCR-AL252005_Wilma.pdf). The deadliest Atlantic basin hurricane of the past 500 years devastated the Caribbean in October 1780, with approximately 22000 deaths occurring in the Lesser Antilles [*Rappaport and Fernandez-Partagas*, 1996].

[3] Previous research has investigated large-scale patterns associated with active seasons in the Caribbean [*Gray*, 1984; *Jury and Enfield*, 2010; *Klotzbach*, 2011]. It has been demonstrated that La Niña conditions in the tropical eastern Pacific and its concomitant reduction in low-latitude Atlantic basin vertical wind shear and decreased static stability provide more conductive conditions for Caribbean TC development. Late-season Caribbean hurricane activity is known to be suppressed in El Niño years due to increased vertical wind shear [*Klotzbach*, 2011]. Also, *Dunion* [2011] has recently documented a large increase in the number of mid-level dry air intrusions into the Caribbean in Octobers of El Niño years. These mid-level dry air intrusions are associated with a dynamic and thermodynamic profile that is unfavorable for TC formation. Novembers are not investigated in his analysis.

[4] A positive phase of the Atlantic Multidecadal Oscillation (AMO) and a larger-than-normal Atlantic Warm Pool (AWP) (defined as the area in the Gulf of Mexico, Caribbean and western tropical Atlantic with sea surface temperatures (SSTs) greater than 28.5°C) are also typically seen with active Caribbean seasons [*Wang and Lee*, 2007; *Jury and Enfield*, 2010; *Klotzbach*, 2011]. While other research has investigated the climate conditions responsible for active Caribbean seasons, there are currently no operational Caribbean forecast models for the October–November period. This manuscript investigates the potential for forecasting late-season Caribbean hurricane activity as a potential addition to the forecast suite currently issued by the Tropical Meteorology Project at Colorado State University [*Klotzbach and Gray*, 2009].

[5] For this forecast scheme, hurricane days (HD) were chosen as the predictand. An HD is defined to be four six-

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hour periods where a TC has maximum one-minute sustained winds of 64 knots or greater. Many other metrics such as named storms, accumulated cyclone energy (ACE) [*Bell et al.*, 2000] or Net Tropical Cyclone (NTC) activity [*Gray et al.*, 1994] could have been chosen with similar levels of predictive skill. For example, HD and ACE correlate at 0.92 from 1982 to 2010. HD was chosen so as to provide a metric that takes into account longevity of stronger TCs in an easily understood quantity.

[6] Section 2 describes the data utilized to investigate late-season Caribbean hurricane activity, while section 3 provides a correlation analysis between predictors and October–November hurricane activity in the Caribbean for the period from 1982 to 2010. Section 4 examines the relationship between October–November values of El Niño-Southern Oscillation (ENSO) and the AWP and their relationship with October–November HD in the Caribbean. Section 5 describes the development of the forecast model, while section 6 discusses the physical fields during the October–November period in the Caribbean that correlate with each predictor. Section 7 examines the skill of the forecast model during the earlier period of 1900–1981 as well as looking at physical fields in the Caribbean that correlate with each predictor during this earlier period. Section 8 concludes the manuscript and provides some ideas for future work.

2. Data

[7] The Atlantic basin hurricane database (HURDAT) was used for all TC calculations [*Jarvinen et al.*, 1984]. HURDAT provides the best estimate of TC location and intensity at each six-hourly interval from 1851 to 2010 and is updated at the end of each TC season. The database has been recently reanalyzed from 1851 to 1930 [*Landsea et al.*, 2008], and statistics in this paper include the reanalyzed data from 1900 to 1930.

[8] The National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature Analysis version 2 (OI SST2) [*Reynolds et al.* 2002] was utilized for SST calculations over the 1982–2010 period. This product is produced every week in real time and includes both in situ and satellite data to arrive at a final SST calculation for each grid box.

[9] The Climate Forecast System Reanalysis (CFSR) was utilized for large-scale atmospheric field calculations over the period from 1982 to 2009 [*Saha et al.*, 2010]. CFSR has significant benefits over earlier reanalysis efforts such as the NCEP/NCAR Reanalysis I [*Kistler et al.*, 2001] due to significantly enhanced vertical (64 levels versus 28 levels) and horizontal resolution (~38 km versus ~200 km). In addition, CFSR includes coupling with an ocean and sea ice model, as opposed to forcing with prescribed SST and sea ice as in the NCEP/NCAR Reanalysis I. Beginning in later 2011, this reanalysis will be updated in near real time allowing for the use of this data set for current-year predictor values.

[10] For earlier-period correlation testing of the October–November forecast model, the 20th Century Reanalysis version 2 was utilized for lower-level and upper-level zonal winds (U) and 700-mb relative humidity (RH) [*Compo et al.*, 2006] over the period from 1900 to 1981. This reanalysis assimilates sea level pressure (SLP), SST and sea ice observations and arrives at its estimated state of the global atmosphere/ocean by using an Ensemble Kalman filter approach.

[11] The Extended Reconstructed SST (ERSST.v3b) data set [*Smith et al.*, 2008] was utilized to examine SSTs from 1900 to 1981. The ERSST.v3b assimilates observed SST data and utilizes statistical methods to fill in areas where data are sparse or non-existent. In general, uncertainties in both SST and low-level wind data sets grow as one goes back further in time.

[12] The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis I was utilized for values of 850-mb U, 200-mb U and 700-mb RH for 2010 [*Kistler et al.*, 2001]. The reanalysis uses a combination of observations and models to provide the best estimate of six-hourly, daily and monthly data at several levels for a large number of atmospheric and oceanic parameters.

[13] All plots and time series calculated from the various reanalysis/SST products were generated from the KNMI Climate Explorer website available online at http://climexp.knmi.nl.

[14] Various statistical significance tests are conducted throughout the remainder of the manuscript. All of these tests are done utilizing a two-tailed Student's t-test, and three levels of significance are examined: 10%, 5% and 1%. The highest level of significance achieved for each test is listed. If a correlation is not significant at the 10% level, it is described as not being significant. Auto-correlation in the various time series is accounted for using the method of *Santer et al.* [2000].

3. October–November Large-Scale Fields/Caribbean HD Correlation Analysis

[15] On a percentage basis, late seasons are more active in the Caribbean, defined as 10–20°N, 88–60°W for this study, than they are for the remainder of the Atlantic basin. Table 1 displays the average ACE accrued by month over the 1948–2010 period for basin-wide activity, Caribbean activity and basin-wide minus Caribbean activity, respectively. There is approximately twice as much ACE activity on a percentage-wise basis in October–November in the Caribbean than there is for the remainder of the North Atlantic (33% versus 18%). It therefore behooves us to investigate active late seasons in the Caribbean in more detail.

[16] Both dynamic and thermodynamic conditions are much more favorable in the Caribbean during the October–November time period then they are further east in the Main Development Region (MDR) (defined as 10–20°N, 60–20°W for this study). Three key physical features known to impact the likelihood of TC formation are 200–850-mb horizontal wind shear, SST, and 700-mb RH [*Gray*, 1968]. Table 2 displays the October and November averaged values of all three parameters for both the Caribbean and the MDR over the 1982–2009 shared base period utilizing the CFSR Reanalysis and NOAA OI SST data sets. All differences between the Caribbean and MDR are statistically significant at the 1% level.

[17] October–November large-scale fields were then correlated over the period from 1982 to 2009 with October–

Table 1. Observed ACE and Percentage of Seasonal ACE Occurring by Month From June–November for Basin-Wide TC Activity, Caribbean TC Activity and Basin-Wide Minus Caribbean TC Activity Over the Period From 1948 to 2010[a]

Month	Basin-Wide ACE	Basin-Wide ACE %	Caribbean ACE	Caribbean ACE %	Basin-Wide − Caribbean ACE	Basin-Wide − Caribbean ACE%
June	1.7	1.7%	0.1	1.1%	1.6	1.8%
July	4.3	4.2%	1.0	5.5%	3.3	3.8%
August	23.5	23.0%	2.9	22.1%	20.6	23.4%
September	50.3	49.2%	5.3	36.4%	45.0	51.1%
October	17.2	16.8%	3.8	25.6%	13.4	15.2%
November	3.8	3.7%	1.0	7.8%	2.8	3.2%

[a] Thirty-three percent of Caribbean ACE occurs during the months of October–November, while only eighteen percent of ACE for the remaining part of the basin occurs during these two months.

November Caribbean basin HD. Figure 1 displays the Pearson product-moment correlation coefficient (referred to as correlation throughout the remainder of the manuscript) with SST, SLP, 850-mb U and 200-mb U from 1982 to 2009. Only correlations that are significant at the 10% level are shaded. The primary correlations are located in the tropical Pacific Ocean and are closely related to ENSO.

[18] Features of note include cooler-than-normal waters in the tropical eastern and central Pacific (Figure 1a), higher-than-normal pressures in the eastern tropical Pacific (Figure 1b), enhanced trade wind strength across the central Pacific (Figure 1c) and upper-level westerly anomalies in the central Pacific (Figure 1d). There is also a moderate negative correlation between October–November trade wind strength in the Caribbean and October–November Caribbean HD. La Niña conditions have been well-documented to enhance storm activity in the Atlantic [*Gray*, 1984] and in the Caribbean [*Klotzbach*, 2011], while reduced trade wind strength is associated with a larger-than-normal AWP [*Wang and Lee*, 2007]. Both of these conditions have been shown to be favorable for an active Caribbean [*Gray*, 1984; *Wang and Lee*, 2007].

[19] It is to be noted that there is virtually no correlation between October–November SSTs in the Caribbean and the number of concurrent Caribbean HD, which may be due to the fact that the storms themselves impact SST anomalies, as there is a strong relationship between these SSTs and October–November Caribbean HD in a precursor sense (as demonstrated in the following sections). Another possible explanation is that in a precursor sense, SSTs in the Caribbean are important, due to their alterations in atmospheric patterns driven by a larger-than-normal AWP. However, these SSTs are not critical on a concurrent basis because SSTs are always warm enough to support TC formation and intensification in this area, similar to what *Chan and Liu* [2004] discuss for the western North Pacific.

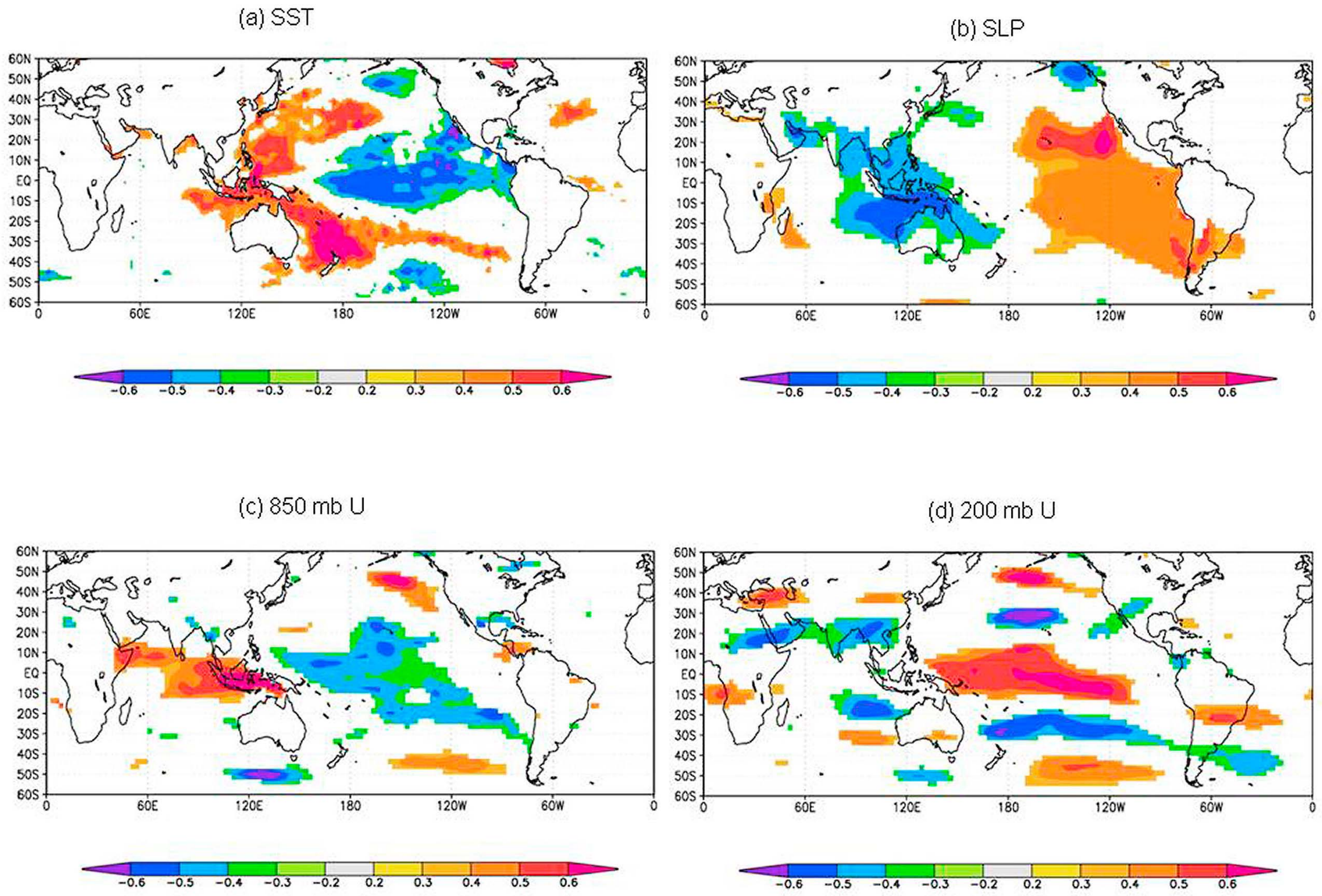
4. Observed Relationship Between October–November ENSO and AWP Conditions and October–November Caribbean Basin HD

[20] All HD at some point in the Caribbean between October 1 and November 30 were counted in this analysis. Years with an October–November–averaged Nino 3.4 index greater than 0.5°C as calculated from the data maintained by the Climate Prediction Center (CPC) (available online at http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices) were classified as El Niño, years with a Nino 3.4 anomaly less than −0.5°C were classified as La Niña, while other years were classified as neutral. The Nino 3.4 region, which is used by the CPC to define ENSO events, has been noted for its pronounced teleconnections with the remainder of the globe [*Barnston et al.*, 1997]. Using this definition, 9 years are classified as La Niña, 10 years are classified as neutral, while the other 10 years are classified as El Niño. Strong relationships between October–November Caribbean HD and ENSO are clearly demonstrated, which is in line with findings by *Klotzbach* [2011]. Table 3 displays the number of HD accrued in the Caribbean during October–November for El Niño, neutral and La Niña years. The ratio of hurricane days occurring in La Niña versus El Niño years is also provided. Since 1981, 27.25 hurricane days have occurred in October–November periods classified as La Niña, while only 0.75 hurricane days have occurred in October–November periods classified as El Niño. Also provided in Table 3 are Caribbean-averaged October–November values of 200–850-mb horizontal wind shear and 700-mb relative humidity. While horizontal wind shear changes between El Niño and La Niña reach approximately 2 ms^{-1}, only small changes are noted in 700-mb relative humidity. No significant differences are noted between neutral and La Niña years for these two particular fields. Only one TC (Hurricane Keith, 2000) was at hurricane strength on September 30 at 1800Z and continued at that intensity into October 1, so pre-existing Caribbean hurricanes at the end of September do not significantly modify the results found here.

[21] As previously discussed, the AWP has also been hypothesized to play an important role in modulating Atlantic basin hurricane activity as discussed by *Wang and Lee* [2007]. The Atlantic Oceanographic and Meteorological Laboratory (AOML) has devised an historical monthly time

Table 2. October and November Area-Averaged Values of SST (°C), 200–850-mb U (ms^{-1}) and 700-mb RH (%) for the Caribbean and MDR

Location	SST	200–850-mb U	700-mb RH
		October	
Caribbean	28.8	7.2	67%
MDR	27.7	12.0	59%
		November	
Caribbean	28.4	12.9	62%
MDR	27.1	22.7	54%


(a) SST

(b) SLP

(c) 850 mb U

(d) 200 mb U

Figure 1. October–November linear correlations between (a) SST, (b) SLP, (c) 850-mb U, and (d) 200-mb U and October–November Caribbean hurricane days (HD) for the period from 1982 to 2009.

Table 3. The Number of October–November Caribbean HD Occurring in El Niño, Neutral and La Niña Years for the Period From 1982 to 2010[a]

ENSO Phase	Oct–Nov HD	Average per Year	Caribbean 200–850-mb U	Caribbean 700-mb RH
El Niño	0.75	0.08	11.1	64%
Neutral	10.25	1.03	9.1	65%
La Niña	27.25	3.03	9.4	65%

[a] The average per-year occurrence, along with October–November–Caribbean-averaged 200–850-mb horizontal wind shear and 700-mb relative humidity (RH) are also provided.

series of the areal extent of the AWP that is maintained in graphical format online at http://www.aoml.noaa.gov/phod/regsatprod/awp/sst_ts.php. Numerical values were provided by Francis Bringas at AOML. When October–November AWPs are stratified based on size, 21.75 October–November Caribbean HD occurred during the 10 largest AWPs, compared with only 3.5 HD in the 10 smallest AWPs. From these relationships, it is clear that both factors significantly modulate late-season activity on a concurrent basis. These two parameters are not significantly correlated with each other ($r = 0.07$) over the period from 1985 to 2010 when both indices are available (Figure 2), indicating that the combination of both parameters provides independent information to the forecast scheme. The focus of this paper now shifts to examining if similar strong relationships between ENSO, the AWP and Caribbean HD are available in a predictive sense.

5. October–November Forecast Model Development

[22] The forecast model was developed using least-squared regression and attempts to maximize the variance explained in October–November Caribbean HD over the 1982–2010 period. Predictors were selected by first examining September, August–September and July–September–averaged linear correlation maps of SST over the 1982–2009 period and looking for areas with statistically significant correlations ($p < 0.10$) (Figure 3). Both the tropical Pacific and tropical Atlantic exhibit strong precursor relationships, with the correlation being the strongest when a three-month average of SSTs is used. Longer-period averages are typically preferred, as they are more robust to shorter-term perturbations, especially in the tropical Atlantic where TCs can alter SSTs significantly on short timescales [e.g., *Yablonsky and Ginis*, 2009; *Rappaport et al.*, 2010]. A simple first attempt at the forecast scheme involved selecting precursor values of ENSO and the AWP to see how well they can predict late-season hurricane activity in the Caribbean.

[23] The July–September–averaged Nino 3.4 index (5°S–5°N, 170°–120°W) was taken as the ENSO precursor, while a July–September–averaged SST value from (10–20°N, 85–50°W) was utilized for the AWP precursor, as the AWP area index time series only extends back to 1985. By utilizing this SST measure instead, the forecast period can be extended back to 1982 and encompass the full NOAA OI SST time series. This SST measure correlated with the July–September AWP time series at 0.91 over the intersecting time period from 1985 to 2010, indicating that they represent largely the same phenomena.

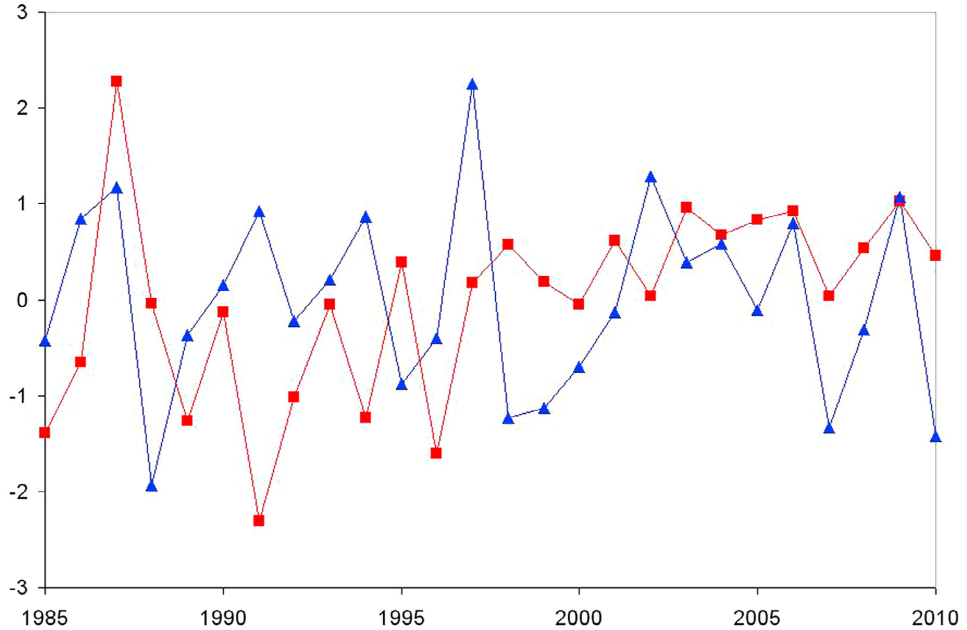
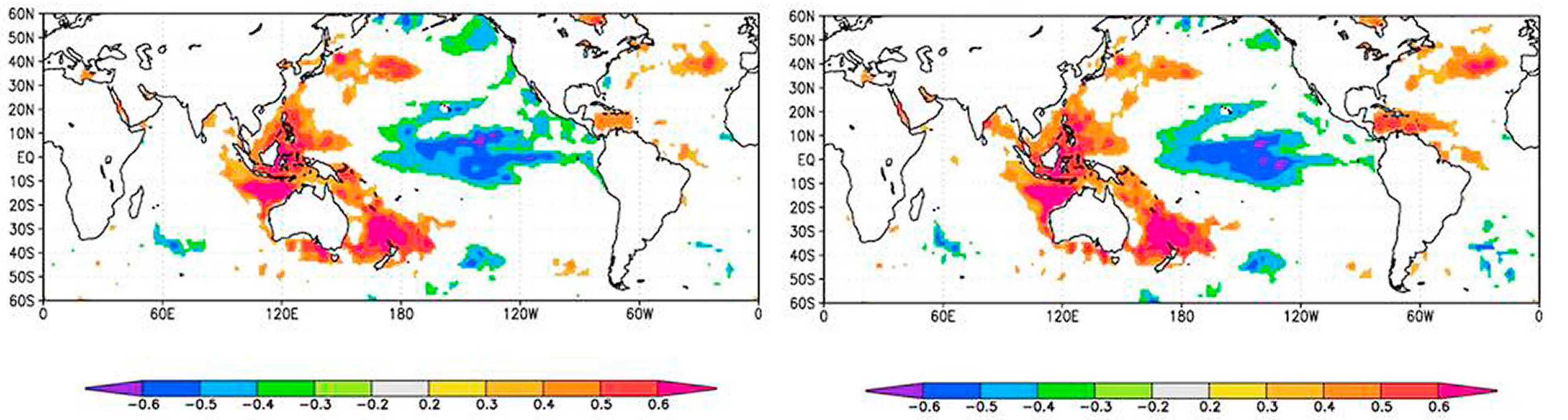


Figure 2. Normalized values of the October–November AWP (red line) and October–November Nino 3.4 (blue line). These two indices are not significantly correlated over the 1985–2010 time period ($r = 0.07$).


(a) September SST

(b) August-September SST

(c) July-September SST

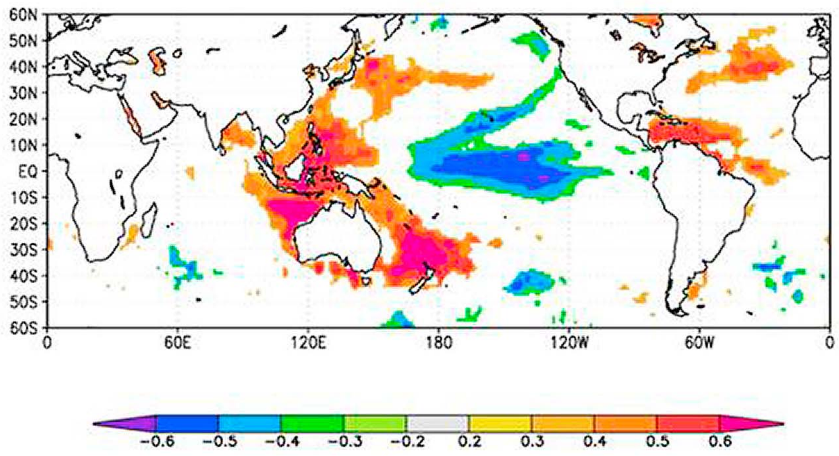


Figure 3. Linear correlations between (a) September SST, (b) August–September SST and (c) July–September SST and October–November Caribbean HD for the period from 1982 to 2009. In general, the correlations appear stronger when the months of July and August are added to September.

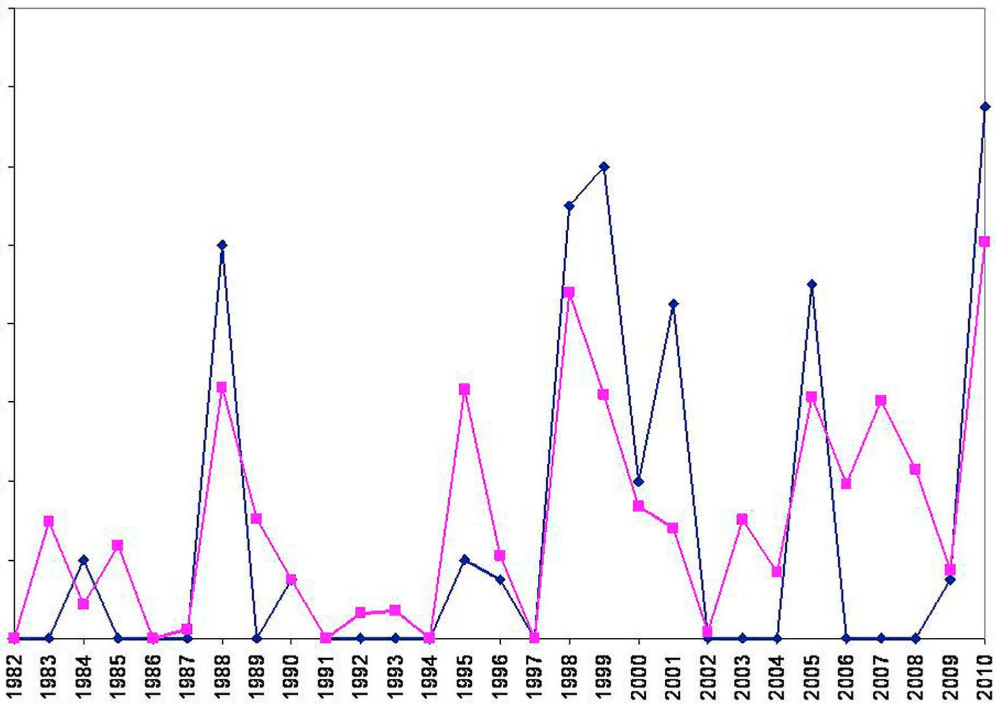


Figure 4. Observed (blue line) versus cross-validated hindcast (pink line) October–November Caribbean HD from 1982 to 2010. The variance explained by the two-predictor model is approximately 58% (r = 0.76).

[24] Both predictors' correlations with October–November HD are significant at the 1% level. The July–September–averaged Nino 3.4 index correlates with October–November HD at −0.63, while the Atlantic SST predictor correlates with October–November HD at 0.63. The two predictors correlate with each other at −0.33, indicating that mostly independent information is included when the second predictor is added.

[25] The predictors were combined using linear regression. If the forecast model called for a negative number of HD, the forecast value was set to zero. When this was done, the combination of both predictors correlated at 0.81 with observed October–November Caribbean HD over the period from 1982 to 2010, with the correlation dropping to 0.76 when a drop-one cross-validation (e.g., jackknife) technique was applied. A jackknife technique is typically regarded as an upper-bound on the potential real-time forecast skill that a model may have [e.g., *Gray et al.*, 1994]. Additional large-scale fields such as SLP, 850-mb U and 200-mb U were investigated for additional predictability beyond that obtained by these two predictors. However, when residual values of HD (e.g., differences between observed and hindcast) were correlated with these global fields, no large-scale areas of correlation were observed (not shown). The MJO has been shown to significantly influence lower- and upper-level wind fields and consequently alter intraseasonal levels of Atlantic basin TC activity [*Klotzbach*, 2010]. Since no large-scale areas of correlation with 850-mb U or 200-mb U were seen, I conclude that the MJO's influence on October–November Caribbean hurricanes must be secondary, or else not evident given the monthly timescale that was examined. The latter is probably more likely; given that the MJO's global propagation time is approximately 40–50 days [*Klotzbach*, 2010].

[26] Equation (1) displays the final forecast equation for October–November Caribbean basin HD, where SST values for both predictors are calculated in °C.

$$\text{Oct}-\text{Nov Carib HD} = -41.5 + (-1.25 * \text{Pac\_SST}) + (2.69 * \text{Atl\_SST}) \qquad (1)$$

[27] The mean absolute error (MAE) of the cross-validated forecast model is significantly less than climatology. The MAE of the model is 1.03 compared with 1.71 for climatology (1.32 HD) – a reduction in MAE of 40%. The forecast model has a reduced MAE compared with climatology in 21 out of 29 years (72%). Figure 4 displays observed October–November Caribbean basin HD versus cross-validated hindcasts from 1982 to 2010. This forecast model will be applied in real-time at the end of September in future years.

6. Relationship Between Predictors and Large-Scale October–November Caribbean Fields

[28] Several physical features have been well-documented to impact tropical cyclogenesis and intensification around the globe and have been used in various forecasting and analysis schemes for over 40 years [e.g., *Gray*, 1968; *DeMaria et al.*, 2001]. Here, the correlation between both predictors and October–November values of SST, SLP, 850-mb U and 200-mb U in the Caribbean (10–20°N, 60–88°W) over the 1982–2010 time period are investigated.

Table 4. Correlation Between Predictors and October–November SST, SLP, 700-mb RH and 200–850-mb U in the Caribbean Over the Period From 1982 to 2010

Predictor	SST	SLP	700-mb RH	200–850-mb U
Tropical Pacific SST	0.09	−0.08	−0.25	0.33
Tropical Atlantic SST	0.76	−0.51	0.55	−0.39

Since both predictors appear to have a strong impact on Caribbean basin TCs during the October–November period, one would expect that both predictors would also correlate with large-scale physical features in the Caribbean during the same period. Table 4 displays the correlation between each predictor and October–November fields in the Caribbean. The Pacific SST predictor, as would be expected, has a significant (10% level) positive correlation with vertical wind shear in the Caribbean. The significant positive correlation verifies studies such as *Gray* [1984] and *Klotzbach* [2011] which documented that vertical wind shear is typically increased in the Caribbean during El Niño years. Significant positive correlations between the Caribbean SST predictor and October–November SST (1% level) and 700-mb RH (1% level) are evident, as well as significant negative correlations between the Caribbean SST predictor and October–November SLP (1% level) and 200–850-mb U (10% level). Similar relationships have been documented on the seasonal level for the Atlantic basin by *Wang and Lee* [2007], and this study confirms that these relationships extend to the late season in the Caribbean.

7. Earlier Period Forecast Verification

[29] The robustness of the forecast model was then tested on earlier-period data from 1900 to 1981. Table 5 displays the correlation between each predictor and October–November Caribbean basin HD over the period from 1900 to 1981 along with sub-period correlations between 1900 and 1943 and 1944–1981, respectively. Surprisingly, both correlations, while of the same sign as the dependent period from 1982 to 2010, have significant drops in correlation value. The AWP predictor is no longer significant, while the ENSO predictor is significant at the 10% level when the full time period is considered. Neither predictor correlates significantly over the 1944–1981 time period, while the ENSO predictor is significant at the 10% level during the 1900–1943 time period. At this point, it is unclear why these correlations fail to reach significant levels during the earlier period. One possibility is that the relationship between ENSO, the AWP and Caribbean basin TC activity may have been different during the earlier period, while another possibility is that estimates of SST in the tropical Pacific and in the Caribbean became inaccurate at some point during the earlier portion of the 20th century. An additional uncertainty is in the TC statistics themselves, as systems during the earlier portion of the 20th century may have been either underestimated or missed due to a lack of satellite data prior to the mid 1960s and aircraft reconnaissance prior to the mid 1940s [*Landsea*, 2007]. However, it appears more likely that one of the first two suggestions is what is actually occurring, since the correlations remain reduced when sub-periods are examined (Table 5). The year 1944 is chosen to separate the two sub-periods, since this is when aircraft reconnaissance began in the Atlantic basin.

Table 5. Correlation Between Predictors and October–November Caribbean Hurricane Days From 1900–1981, 1900–1943, and 1944–1981

Name	Correlation With Oct–Nov Caribbean HD
Tropical Pacific SST (1900–1981)	−0.19
Tropical Atlantic SST (1900–1981)	0.13
Tropical Pacific SST (1900–1943)	−0.27
Tropical Atlantic SST (1900–1943)	0.18
Tropical Pacific SST (1944–1981)	−0.07
Tropical Atlantic SST (1944–1981)	0.22

[30] Table 6 displays correlations between both predictors and October–November large-scale fields over the period from 1900 to 1981. Significant (5% level) positive correlations between the Pacific SST predictor and 200–850-mb U persist, while all correlations between the Caribbean SST predictor and large-scale fields remain significant except for SLP (1% level for SST and 200–850-mb U and 5% level for 700-mb RH). So, it appears that large-scale fields are being modified in a similar manner, despite the lack of the relationship between the predictor and earlier-period HD. The extensive research that has been conducted documenting both ENSO and the AWP and their impacts on Atlantic basin hurricanes gives increased confidence that the strong physical basis of this model should provide significant levels of predictability in future years.

8. Conclusions and Future Work

[31] A seasonal forecast model has been developed to predict October–November Caribbean HD. One of the predictors is strongly related to ENSO, while the other is strongly related to the AWP, both of which have been studied extensively for their relationships with Atlantic basin TC activity. These strong physical relationships should help to prevent screening error issues discussed by *DelSole and Shukla* [2009]. The model explains approximately 58% of the variance over the period from 1982 to 2010 when a drop-one cross-validation technique is applied. Significant correlations at the 1% level exist between both predictors and hurricane activity, while significant correlations are also documented between both predictors and large-scale fields in the Caribbean during the October–November period that have been well-documented to impact storms in this region.

[32] While correlations between both predictors and large-scale fields remain significant during an earlier period from 1900 to 1981, the correlations between predictors and October–November Caribbean basin HD degrade considerably. Given the strong physical relationships that have been demonstrated

Table 6. Correlation Between Predictors and October–November SST, SLP, 700-mb RH and 200–850-mb U in the Caribbean Over the Period From 1900 to 1981

Predictor	SST	SLP	700-mb RH	200–850-mb U
Tropical Pacific SST	0.37	0.06	−0.11	0.30
Tropical Atlantic SST	0.83	−0.08	0.36	−0.38

in this paper as well as in previous research by *Gray* [1984], *Wang and Lee* [2007], *Klotzbach* [2011] and others, the author has confidence that this scheme will likely exhibit real-time forecast skill. The statistical model outlined in this paper will be incorporated into the forecast suite of products currently issued by the Tropical Meteorology Project and will be available online at the end of September in future years at http://tropical.atmos.colostate.edu.

[33] In the future, the author intends to investigate additional portions of the Atlantic basin (e.g., the Main Development Region, the Gulf of Mexico) and various time periods (e.g., June–July, August–October) to determine if similar skill can be obtained for predicting activity in these regions and over these time periods.

[34] **Acknowledgments.** I would like to thank William Gray and Eric Blake for many helpful discussions on Caribbean TC activity. I would like to thank the three anonymous reviewers for helpful comments that considerably improved the manuscript.

References

Barnston, A. G., M. Chelliah, and S. B. Goldenberg (1997), Documentation of a highly ENSO-related SST region in the equatorial Pacific, *Atmos. Ocean*, *35*, 367–383.

Bell, G. D., M. S. Halpert, R. C. Schnell, R. W. Higgins, J. Lawrimore, V. E. Kousky, R. Tinker, W. Thiaw, M. Chelliah, and A. Artusa (2000), Climate assessment for 1999, *Bull. Am. Meteorol. Soc.*, *81*, 1–50, doi:10.1175/1520-0477(2000)081<1328:CAF>2.3.CO;2.

Chan, J. C. L., and K. S. Liu (2004), Global warming and western North Pacific typhoon activity from an observational perspective, *J. Clim.*, *17*, 4590–4602, doi:10.1175/3240.1.

Compo, G. P., J. S. Whitaker, and P. D. Sardeshmukh (2006), Feasibility of a 100 year reanalysis using only surface pressure data, *Bull. Am. Meteorol. Soc.*, *87*, 175–190, doi:10.1175/BAMS-87-2-175.

DelSole, T., and J. Shukla (2009), Artificial skill due to predictor screening, *J. Clim.*, *22*, 331–345, doi:10.1175/2008JCLI2414.1.

DeMaria, M., J. A. Knaff, and B. H. Connell (2001), A tropical cyclone genesis parameter for the tropical Atlantic, *Weather Forecasting*, *16*, 219–233, doi:10.1175/1520-0434(2001)016<0219:ATCGPF>2.0.CO;2.

Dunion, J. P. (2011), Rewriting the climatology of the tropical North Atlantic and Caribbean Sea atmosphere, *J. Clim.*, *24*, 893–908, doi:10.1175/2010JCLI3496.1.

Gray, W. M. (1968), Global view of the origin of tropical disturbances and storms, *Mon. Weather Rev.*, *96*, 669–700, doi:10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2.

Gray, W. M. (1984), Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences, *Mon. Weather Rev.*, *112*, 1649–1668, doi:10.1175/1520-0493(1984)112<1649:ASHFPI>2.0.CO;2.

Gray, W. M., C. W. Landsea, P. W. Mielke, and K. J. Berry (1994), Predicting Atlantic basin seasonal tropical cyclone activity by 1 June, *Weather Forecasting*, *9*, 103–115, doi:10.1175/1520-0434(1994)009<0103:PABSTC>2.0.CO;2.

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis (1984), A tropical cyclone data tape for the North Atlantic basin, 1886–1983: Contents, limitations, and uses, *Tech. Rep. NWS NHC 22*, 21 pp., NOAA, Miami, Fla.

Jury, M. R., and D. B. Enfield (2010), Environmental patterns associated with active and inactive Caribbean hurricane seasons, *J. Clim.*, *23*, 2146–2160, doi:10.1175/2009JCLI3201.1.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267, doi:10.1175/1520-0477(2001)082<0247:TNNYRM>2.3.CO;2.

Klotzbach, P. J. (2010), On the Madden–Julian oscillation–Atlantic hurricane relationship, *J. Clim.*, *23*, 282–293, doi:10.1175/2009JCLI2978.1.

Klotzbach, P. J. (2011), The influence of El Niño–Southern Oscillation and the Atlantic multidecadal oscillation on Caribbean tropical cyclone activity, *J. Clim.*, *24*, 721–731, doi:10.1175/2010JCLI3705.1.

Klotzbach, P. J., and W. M. Gray (2009), Twenty-five years of Atlantic basin seasonal hurricane forecasts, *Geophys. Res. Lett.*, *36*, L09711, doi:10.1029/2009GL037580.

Landsea, C. W. (2007), Counting Atlantic tropical cyclones back to 1900, *Eos Trans. AGU*, *88*(18), 197, doi:10.1029/2007EO180001.

Landsea, C. W., et al. (2008), A reanalysis of the 1911–20 Atlantic hurricane database, *J. Clim.*, *21*, 2138–2168, doi:10.1175/2007JCLI1119.1

Rappaport, E. N., and J. Fernandez-Partagas (1996), The deadliest Atlantic tropical cyclones: 1492–1996, *Tech. Rep. NWS NHC 47*, Natl. Hurricane Cent., Miami, Fla.

Rappaport, E. N., J. L. Franklin, A. B. Schumacher, M. DeMaria, L. K. Shay, and E. J. Gibney (2010), Tropical cyclone intensity change before U.S. Gulf Coast landfall, *Weather Forecasting*, *25*, 1380–1396, doi:10.1175/2010WAF2222369.1.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang (2002), An improved in situ and satellite SST analysis for climate, *J. Clim.*, *15*, 1609–1625, doi:10.1175/1520-0442(2002)015<1609:AIISAS>2.0.CO;2.

Saha, S., et al. (2010), The NCEP Climate Forecast System Reanalysis, *Bull. Am. Meteorol. Soc.*, *91*, 1015–1057, doi:10.1175/2010BAMS3001.1.

Santer, B. D., T. M. L. Wigley, J. S. Boyle, D. J. Gaffen, J. J. Hnilo, D. Nychka, D. E. Parker, and K. E. Taylor (2000), Statistical significance of trends and trend differences in layer-averaged atmospheric temperature time series, *J. Geophys. Res.*, *105*(D6), 7337–7356, doi:10.1029/1999JD901105.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore (2008), Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006), *J. Clim.*, *21*, 2283–2296, doi:10.1175/2007JCLI2100.1.

Wang, C., and S.-K. Lee (2007), Atlantic warm pool, Caribbean low-level jet, and their potential impact on Atlantic hurricanes, *Geophys. Res. Lett.*, *34*, L02703, doi:10.1029/2006GL028579.

Yablonsky, R. M., and I. Ginis (2009), Limitation of one-dimensional ocean models for coupled hurricane-ocean model forecasts, *Mon. Weather Rev.*, *137*, 4410–4419, doi:10.1175/2009MWR2863.1.

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