GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L16710, doi:10.1029/2011GL048603, 2011

A simplified Atlantic basin seasonal hurricane prediction scheme from 1 August

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Received 20 June 2011; revised 19 July 2011; accepted 19 July 2011; published 25 August 2011.

[1] The Tropical Meteorology Project at Colorado State University has issued seasonal forecasts for Atlantic basin hurricane activity in early August since 1984. This paper proposes a simplified scheme, using a combination of two surface predictors selected from the newly-developed Climate Forecast System Reanalysis (CFSR) as well as a dynamical forecast for El Niño-Southern Oscillation (ENSO) from the European Centre for Medium-Range Weather Forecasts (ECMWF). These three predictors in combination explain approximately 72% of the cross-validated variance in post-1 August Net Tropical Cyclone (NTC) activity over the hindcast period from 1982–2010. While uncertainties in the data grow as one goes back further in time, all three predictor correlations remain significant with NTC when tested on data from 1900–1981. These predictors are also shown to correlate with August-October physical features across the Atlantic Main Development region known to impact hurricane activity.

Citation: Klotzbach, P. J. (2011), A simplified Atlantic basin seasonal hurricane prediction scheme from 1 August, *Geophys. Res. Lett.*, *38*, L16710, doi:10.1029/2011GL048603.

1. Introduction

[2] The Tropical Meteorology Project (TMP) at Colorado State University has issued Atlantic basin seasonal hurricane forecasts in early August since 1984 [*Gray*, 1984]. While the Atlantic hurricane season officially starts on 1 June, approximately 92% of all Net Tropical Cyclone (NTC) activity [*Klotzbach*, 2007] occurs after 1 August based on National Hurricane Center (NHC) statistics over the period from 1982–2010. NTC is defined to be the sum of named storms, named storm days, hurricanes, hurricane days, major hurricanes and major hurricane days normalized by their 1950–2000 climatological averages, where 100 NTC units by definition represents the average 1950–2000 hurricane season [*Gray et al.*, 1994]. Therefore, a seasonal forecast issued on 1 August should still have considerable value. Previous August forecast models have been described in detail by *Gray et al.* [1993] and *Klotzbach* [2007]. These models have shown moderate levels of real-time forecast skill [*Klotzbach and Gray*, 2009]. A correlation of 0.65 has been achieved between predicted versus observed post-1 August hurricanes from 1984–2010, using the verification spreadsheet provided by the TMP at http://tropical.atmos.colostate.edu.

[3] Over the past several years, new reanalysis products have been made available, while the skill of dynamical forecasts has continued to improve. Given these two developments, I re-examine the August statistical forecast model to see if additional skill improvements can be made beyond those demonstrated by *Klotzbach* [2007]. Section 2 describes the data utilized to develop this new forecast model, while Section 3 describes the predictor selection process along with the hindcast skill of the predictors selected over the period from 1982–2010. A discussion of how each of the predictors is likely related to Atlantic basin tropical cyclone (TC) activity is discussed in Section 4, while Section 5 examines the skill of these predictors over the earlier part of the 20th century from 1900–1981. Section 6 concludes the manuscript and provides some ideas for future work.

2. Data

[4] All TC statistics are calculated from the NHC's Best Track file available online at http://www.nhc.noaa.gov/data/hurdat/tracks1851to2010_atl_reanal.txt. All TCs from 1851–1930 have recently been reanalyzed [*Landsea et al.*, 2008], and these reanalyzed storms from 1900–1930 are included in the analysis that follows.

[5] Recently, the National Centers for Environmental Prediction (NCEP) has completed the Climate Forecast System Reanalysis (CFSR) [*Saha et al.*, 2010]. The CFSR is considered to be an improvement upon earlier reanalysis products such as the NCEP/NCAR Reanalysis I [*Kistler et al.*, 2001], due to increases in vertical and horizontal resolution, improved data assimilation techniques, and coupling between the atmosphere and ocean and sea ice models. CFSR data is currently available from 1979–2009, with plans to have the reanalysis available in real-time in future years. Currently, NCEP/NCAR I Reanalysis data are utilized for 2010 predictor values as well as for 1948–1981 for atmospheric variables.

[6] NOAA Optimum Interpolation (OI) sea surface temperature (SST) version 2 data are utilized from 1982-present [*Reynolds et al.*, 2002]. NOAA OI SST version 2 utilizes a blend of in situ and satellite observations to arrive at its analyzed values. In order to test predictors on the earlier part of the 20th century, NOAA's Extended Reconstructed SST version 3b was utilized [*Smith et al.*, 2008]. This dataset uses in situ observations and statistical techniques that attempt to allow for a reliable reconstruction given sparse observations as one goes back further in time.

[7] The 20th Century Reanalysis [*Compo et al.*, 2011] was utilized to verify predictor skill from 1900–1947. This reanalysis product assimilates surface pressure and sea level pressure every six hours and uses the Climate Forecast System's atmospheric component to generate estimates of the state of the atmosphere in the vertical.

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Table 1. Predictors Selected for the Post-1 August NTC Forecast[a]

Predictor Type	Predictor Location	Linear Correlation With NTC (1982–2010)
June-July SST	20-50°N, 35-15°W	0.67
July 10 meter U	10-17.5°N, 80-40°W	0.83
ECMWF September SST Forecast (Model Initialized 1 July)	5°S-5°N, 170-120°W	−0.49

[a] Also presented are the linear correlations between each individual predictor and post-1 August NTC.

[8] One of the predictors selected for the August forecast model involves an SST prediction for the Nino 3 region (5°N-5°S, 170-120°W) from the European Centre for Medium Range Weather Forecasts (ECMWF). This forecast is based off of the ECMWF seasonal forecast system 3 [*Stockdale et al.*, 2011] which has shown skill at forecasting ENSO events several months in the future.

3. August Seasonal Forecast Model Development

[9] In order to develop a forecast model for seasonal TC activity, correlation maps were constructed between post-1 August NTC activity and June-July values of SST, sea level pressure (SLP) and 10-meter zonal winds (U). These low-level fields were considered, as estimates of surface parameters are likely more reliable than upper-level parameters extending back to 1900, given that these surface parameters are somewhat constrained by observations, while upper-level fields are virtually completely model-driven [e.g., *Klotzbach*, 2007]. Two-month averages were considered (e.g., June-July) as well as single-month (June and July) values to optimize the hindcast skill achievable by this particular forecast scheme. Predictors were added to the scheme using a stepwise technique, and they were only kept in the scheme if they added at least an additional three percent of the variance explained over the hindcast period from 1982–2010. In addition to these low-level observed fields, predicted values for the Nino 3 region and Nino 3.4 region from the 1 July integration of the ECMWF model were considered. The final hindcast for NTC was calculated by placing the three predictors in a linear regression model and then applying a drop-one cross validation approach. A drop-one cross-validation approach leaves the year out of the forecast scheme that you are trying to predict, and consequently, is generally considered an upper-bound on real-time forecast skill [*Gray et al.*, 1993].

[10] Table 1 displays the predictors that were selected using the approach that has just been outlined. The exact regions selected for each predictor were chosen after examining the correlation maps over the period from 1982–2010 and finding areas that had the strongest correlation with NTC over this time period. Also provided is each predictor's linear correlation with NTC over the developmental period from 1982–2010. All predictors' correlations with NTC are statistically significant at the 99% level, using a two-tailed Student's t-test and assuming that each year represents an individual degree of freedom. Table S1 in the auxiliary material displays an inter-correlation matrix between the three predictors.[1] While there is some inter-correlation between predictors, the significant previous research documenting how each of these individual predictors relates to TC activity should help result in stable predictive equations. In addition, the inter-correlation between predictors never exceeds |0.54|, indicating that 70% of the variance explained by each predictor is independent of any other single predictor in the scheme.

[11] Figure S1 displays the cross-validated hindcast post-1 August NTC versus observations from 1982–2010 along with cross-validated hindcasts from the earlier model described by *Klotzbach* [2007]. The cross-validated hindcast for the new model correlates with observations at 0.85 over this time period, explaining over 70% of the variability of post-1 August NTC. If the earlier model discussed by *Klotzbach* [2007] was used given the same forecast development procedure (e.g., cross-validated hindcasts using the CFSR and NOAA OI SST datasets), the model correlates at 0.73, explaining just over 50% of the variability. Consequently, the new forecast scheme shows improvement over the old scheme, explaining approximately 20% more of the variability from climatology and showing a smaller absolute error than the old scheme in 19 out of 29 years (66%).

[12] The model shows impressive improvements over several no-skill metrics (1982–2010 climatology, previous three-year mean, previous five-year mean and previous ten-year mean) over the 29-year period (Table S2). Mean absolute error (MAE), defined as the absolute value of the observed NTC minus the forecast NTC, using the newly-developed model are approximately 50% less than the no-skill metrics evaluated. The model had a lower MAE than the no-skill metrics in between 20 and 24 of the 29 years, depending on which particular no-skill metric was being evaluated.

4. Physical Relationships between Predictors and Atlantic Basin TC Activity

[13] Each of the predictors listed in Table 1 has a well-documented relationship with Atlantic TC activity. Table 2 displays linear correlations from 1982–2010 between each predictor and August-October SST, SLP and 200-850-mb zonal shear across the Main Development Region (10-20°N, 85-20°W). All three of these features have been discussed extensively in the literature to create an environment either more or less conducive for cyclogenesis [e.g., *Gray*, 1984; *Kossin and Vimont*, 2007]. All linear correlations between each predictor and August-October large-scale fields of SST, SLP and 200-850-mb zonal shear are statistically significant at the 95% level using a two-tailed Student's t-test, except between Predictor 3 and August-October SST. The lack of a relationship here is to be expected, since

Table 2. Correlation Between Predictors and August-October-Averaged SST, SLP and 200-850-mb Zonal Shear Across the Main Development Region (10-20°N, 85-20°W) Over the Period From 1982–2010[a]

Predictor Number and Name	SST	SLP	200-850 MB dU/dz
1 Subtropical Atlantic SST	*0.70*	*−0.58*	*−0.52*
2 Tropical Atlantic U	*0.59*	*−0.58*	*−0.72*
3 ECMWF Nino 3 Forecast	−0.10	*0.35*	*0.46*

[a] Correlations that are significant at the 95% level using a two-tailed Student's t-test are highlighted in italics.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048603.

Table 3. Correlation Between Predictors and Post-1 August NTC Over the Period From 1900–1981, 1900–1947, and 1948–1981, Respectively

Predictor Number and Name	NTC
1900–1981	
1 Subtropical Atlantic SST	0.31
2 Tropical Atlantic U	0.41
3 Observed September Nino 3	−0.32
1900–1947	
1 Subtropical Atlantic SST	0.34
2 Tropical Atlantic U	0.50
3 Observed September Nino 3	−0.46
1948–1981	
1 Subtropical Atlantic SST	0.25
2 Tropical Atlantic U	0.48
3 Observed September Nino 3	−0.25

ENSO's impacts on Atlantic SSTs tend to be most evident during the spring [*Alexander et al.*, 2002].

[14] It is critical that a solid physical understanding of how each predictor relates to Atlantic TC activity is documented, in order to prevent selecting predictors that correlate by chance. Each of the predictors discussed below are clearly tied to large-scale physical modes which have been documented in a variety of papers to impact Atlantic TC activity on a seasonal basis. Physical hypotheses for how each individual predictor likely is related to Atlantic TC activity are now discussed.

4.1. Predictor 1: June-July SST (20-50°N, 35-15°W)

[15] A similar predictor was utilized in the previous August seasonal forecast model [*Klotzbach*, 2007]. Anomalously warm SSTs in the subtropical North Atlantic are associated with a positive phase of the Atlantic Meridional Mode (AMM), a northward-shifted Intertropical Convergence Zone, and consequently, reduced trade wind strength [*Kossin and Vimont*, 2007]. Weaker trade winds are associated with less mixing and upwelling, which results in warmer tropical Atlantic SSTs during the August-October period. This strong relationship between Predictor 1 and August-October tropical Atlantic SSTs is demonstrated by the correlation of 0.70 between the two parameters.

4.2. Predictor 2: July 10 Meter U (10-17.5°N, 80-40°W)

[16] Low-level trade wind flow has been utilized as a predictor in seasonal forecasting systems for the Atlantic basin [*Lea and Saunders*, 2004]. When the trades are weaker-than-normal, SSTs across the tropical Atlantic tend to be elevated, and consequently a large-than-normal Atlantic Warm Pool is typically observed [*Wang and Lee*, 2007]. A larger AWP also correlates with reduced vertical shear across the tropical Atlantic. Predictor 2 has a −0.72 correlation with August-October-averaged 200-850-mb zonal shear.

4.3. Predictor 3: ECMWF September SST Forecast for Nino 3 (Model Initialized on 1 July)

[17] The relationship between ENSO and Atlantic TCs has been well-documented over more than 25 years [e.g., *Gray*, 1984; *Tang and Neelin*, 2004; *Klotzbach*, 2011]. When El Niño is underway in the tropical Pacific during the Atlantic hurricane season, the Walker Circulation tends to weaken and shift eastward, imparting increased upper-level westerly wind anomalies, consequently increasing the shear across the tropical Atlantic [*Gray*, 1984]. In addition, anomalous sinking and drying take place across the tropical Atlantic in El Niño years, creating a more stable atmosphere which is less conducive for TC formation [*Tang and Neelin*, 2004]. ECMWF's seasonal forecast system 3 [*Stockdale et al.*, 2011] has shown significant skill at predicting ENSO events several months in the future. According to hindcast data from 1982–2010 provided by F. Vitart (personal communication, 2011), a Nino 3 forecast from the ECMWF system 3 model initialized on 1 July correlates with observed September Nino 3 at 0.90. As would be expected given this discussion, Predictor 3 has a significant correlation with August-October-averaged 200-850-mb zonal shear across the tropical Atlantic.

5. Predictor Skill Over the 1900–1981 Time Period

[18] The skill of the three predictors is now examined over the earlier period from 1900–1981. Earlier in the 20th century, there is more uncertainty in both the record of TCs and the large-scale atmospheric/oceanic fields, but if correlations between predictors and TCs remain significant over this earlier period, it adds increased confidence that the forecast will likely show robust skill in a prediction mode. Since the hindcast data from the ECMWF is only available from around 1980 to the present, I utilize observed September Nino 3 SST for the earlier-period testing on Predictor 3.

[19] Table 3 displays the linear correlation between each predictor and Atlantic TC activity over the period from 1900–1981, and over two sub-periods: 1900–1947 and 1948–1981. The time period was divided between the 1947 and 1948 hurricane seasons, due to the fact that the NCEP/NCAR Reanalysis dataset which was utilized for the large-scale field analysis in the upcoming discussion began in 1948. All predictor correlations with NTC are statistically significant at the 95% level using a one-tailed Student's t-test over the full period from 1900–1981. A one-tailed Student's t-test was used for all three predictors, as they have been well-documented to be strongly related to Atlantic TCs.

[20] The correlations are somewhat greater over the period from 1900–1947 than they are from 1948–1981. Predictor 1 and Predictor 3's correlation with NTC is only significant at the 90% level during the more recent period. Given the strong physical relationships between both predictors and Atlantic TC activity (e.g., *Klotzbach* [2007] for Predictor 1 and *Gray* [1984] for Predictor 3), there is confidence that the predictors will likely have a continued robust relationship with TC activity for the foreseeable future.

[21] As was done in Section 4 for the period from 1982–2010, correlations between each predictor and August-October large-scale fields are now examined (Table S3). Similar strong relationships between individual predictors and MDR-averaged vertical wind shear are seen over the full 1900–1981 period. The strong correlation between Predictor 1 and August-October SST across the MDR persists. Correlations with other MDR parameters are somewhat weaker, although several are still significant at the 95% level. The degradation in correlation is expected, given the increased uncertainty in the observations of predictor values and August-October large-scale fields as one goes back further in time. The continued statistically significant relationships

between predictors and overall TC activity as well as between predictors and large-scale August-October fields give increased confidence in the utility of this prediction scheme in future years.

6. Conclusions and Future Work

[22] This paper demonstrates that a three predictor model using a measure of SST in the subtropical Atlantic, trade wind strength in the tropical Atlantic, and a prediction of the Nino 3 region in the tropical Pacific from the ECMWF model can explain over 70% of the variability in post-1 August NTC from 1982–2010 by using a cross-validated linear regression model. Each of these three predictors also correlated strongly with August-October physical features known to impact Atlantic TC activity, such as tropical Atlantic SST, SLP and 200-850-mb vertical wind shear. While the correlations were degraded somewhat during the earlier period from 1900–1981, predictor correlations with NTC as well as August-October physical features generally remained statistically significant.

[23] I intend to redo the TMP's early April and early June seasonal forecasts using a similar methodology to what was done for the early August forecast, including investigating the utility of the ECMWF's forecast for September ENSO conditions. As dynamical forecasts continue to improve and additional historical climate datasets become available for improved statistical analysis, the development of additional statistical/dynamical hybrid seasonal forecast schemes is likely.

[24] **Acknowledgments.** Valuable discussions on Atlantic seasonal hurricane prediction have been held with Eric Blake, William Gray, John Knaff, Chris Landsea, Brian McNoldy and Jonathan Vigh.

[25] The Editor thanks the two anonymous reviewers.

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