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Quantifying the Probability and Causes of the Surprisingly Active 2018 North Atlantic Hurricane Season

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Key Points:
- The 2018 North Atlantic hurricane season witnessed activity 25% above the long-term average, due mainly to high activity in the subtropics
- The environmental fields that explain most variance in long-term hurricane activity all predicted a below-normal 2018 hurricane season
- The 2018 hurricane season highlights the need for seasonal hurricane outlooks to be issued in terms of probability of exceedance

Supporting Information:
- Supporting Information S1

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Abstract The 2018 North Atlantic hurricane season was a destructive season with hurricanes Florence and Michael causing significant damage in the southeastern United States. In keeping with most destructive hurricane seasons, basinwide tropical cyclone activity was above average in 2018—by ~25% for named storm numbers, hurricane numbers, and Accumulated Cyclone Energy (ACE). In contrast to this above-normal activity, the August–September tropical environmental fields that explain ~50% of the variance in Atlantic basin hurricane activity between 1950 and 2017 anticipated a well below-average 2018 hurricane season. The surprisingly large mismatch between the observed and replicated levels of hurricane activity in 2018 is an extreme example of the uncertainty inherent in seasonal hurricane outlooks and highlights the need for these outlooks to be issued in terms of probability of exceedance. Such probabilistic information would better clarify the uncertainty associated with hurricane outlooks to the benefit of users. With retrospective knowledge of the August–September 2018 key tropical environmental fields, the chance that the observed 2018 Atlantic hurricane activity would occur is about 5%. The reasons for the surprisingly high hurricane activity in 2018 are a hurricane outbreak in early September and, in particular, the occurrence of unusually high tropical cyclone activity in the subtropical North Atlantic. The hyperactive subtropical activity was not anticipated because contemporary statistical models of seasonal Atlantic hurricane activity lack skill in anticipating subtropical ACE compared to tropical ACE.

Plain Language Summary Seasonal outlooks for North Atlantic hurricane activity contribute to the anticipation of risk for insurance companies, other weather-sensitive businesses, and local and national governments. However, the uncertainty associated with such forecasts is often unclear. This reduces their benefit and contributes to the perception of forecast "busts." The issue is highlighted by the destructive and surprising 25% above-average 2018 Atlantic hurricane season. Retrospective examination of the key August–September 2018 environmental fields that explain ~50% of long-term Atlantic hurricane activity shows that all were consistent with a well below-average 2018 hurricane season. A below-normal season was also anticipated by hurricane outlooks issued in early August 2018. The large mismatch between the observed and replicated levels of hurricane activity in 2018 is an extreme example of the uncertainty inherent in hurricane outlooks. We show that this uncertainty may be properly clarified by expressing outlooks in terms of probability of exceedance. The likelihood that the observed 2018 hurricane activity would occur with retrospective knowledge of the key environmental fields is about 5%. Hyperactive storm activity in the subtropical North Atlantic contributed to the surprisingly active 2018 hurricane season. The unusual subtropical activity was not anticipated because statistical models lack skill in anticipating such activity.

1. Introduction

North Atlantic (hereafter Atlantic) hurricane activity exhibits large interannual variability. In the geostationary satellite era (since 1966) the annual number of Atlantic hurricanes has ranged from 2 in 1982 and 2013 to 15 in 2005 (Landsea & Franklin, 2013). Better understanding of the nature and causes of this variability will help the forecasting of hurricane activity on timescales from subseasonal to multidecadal. It will also assist in the detection and attribution of changes in hurricane activity due to anthropogenic climate change. However, the value of this greater understanding will be diminished without more robust quantification and better communication of forecast uncertainty. For example, seasonal outlooks of Atlantic hurricane activity contribute to the anticipation of risk for weather-sensitive businesses. The robust assessment of

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risk requires a full and clear probabilistic quantification of forecast uncertainty with the forecast issued in terms of probability of exceedance (PoE). In this way the chance of each hurricane number/activity outcome occurring is clear. At present the full uncertainty in seasonal (and other) hurricane forecasts is frequently either missing, unclear, or calculated incorrectly. This situation arises from the common incorrect practice of computing uncertainties based on unstandardized data and from presenting forecasts either in deterministic form with no uncertainty information or in tercile probability form with incomplete uncertainty information.

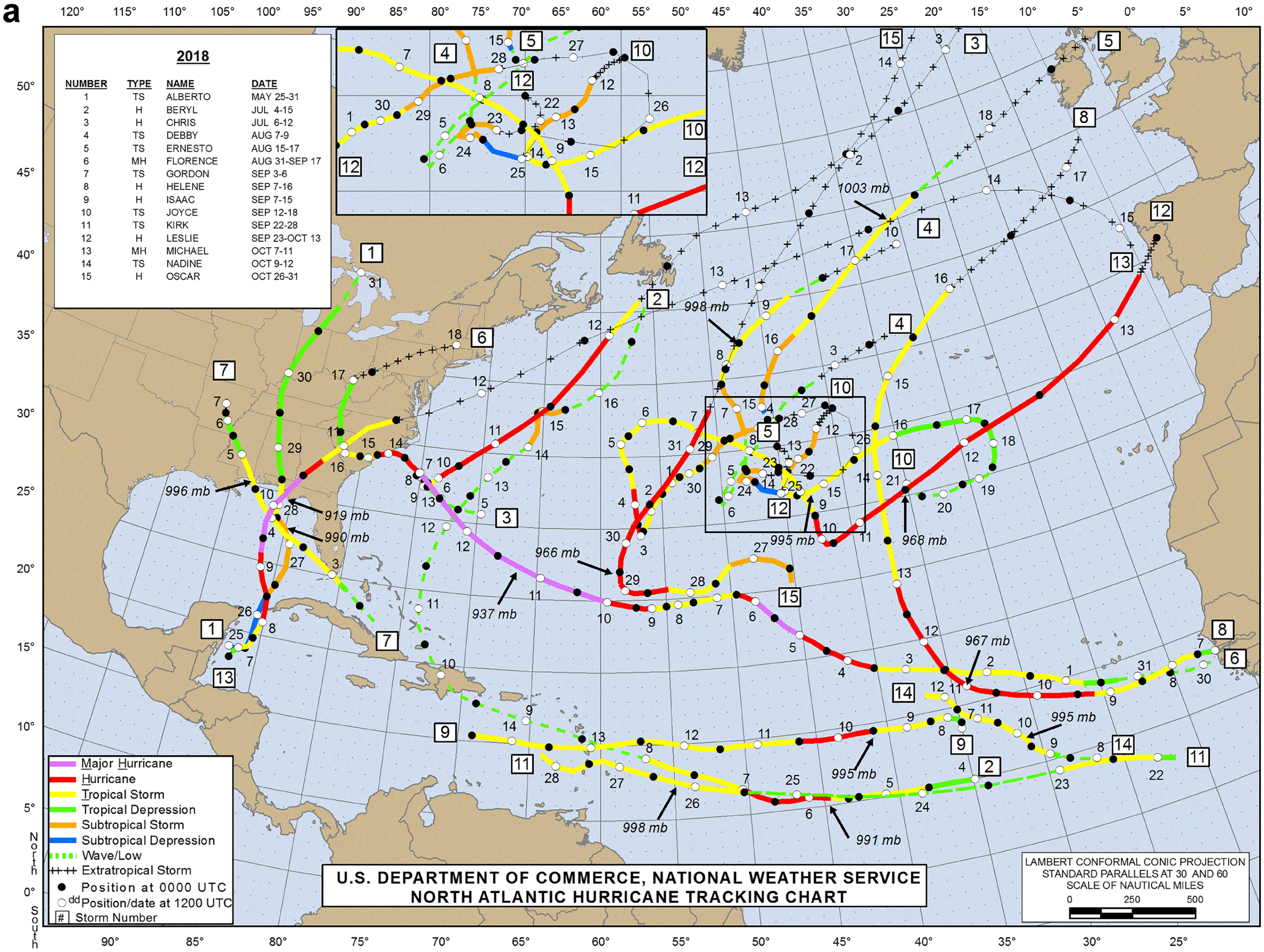
The 2018 Atlantic hurricane season highlights the need to improve the understanding and communication of the uncertainty in seasonal hurricane outlooks. This is due to the large mismatch that occurred between the observed and retrospectively anticipated (and forecast) levels of hurricane activity in 2018. Here we highlight the nature of this uncertainty by clarifying its origin in 2018 and by describing how the uncertainty may be quantified and communicated in terms of PoE to provide clear and full forecast transparency. The manuscript is structured as follows. Section 2 presents an overview of the 2018 Atlantic hurricane season and summarizes how well activity was predicted. Section 3 describes the environmental fields, data sources, and analysis methods that underpin our analysis. Results from our robust deterministic and exceedance probability modeling of the 2018 hurricane season are described, respectively, in sections 4 and 5. Section 6 describes the factors that contributed to the unexpectedly active 2018 hurricane season. Section 7 assesses the prospects for improving the precision of statistical hurricane outlooks based upon the findings of section 6. The manuscript concludes (section 8) by recommending that forecast PoE plots are included as part of future hurricane outlooks.

2. The 2018 Atlantic Hurricane Season

The 2018 Atlantic hurricane season was a destructive season with hurricanes Florence and Michael causing significant damage in the southeastern United States. Hurricane Florence made landfall as a Category 1 hurricane near Wrightsville Beach, North Carolina, and caused destructive freshwater flooding across the Carolinas. Hurricane Michael made landfall as a Category 5 hurricane near Mexico Beach, Florida, and produced devastating winds and storm surge near the coast, and rain and wind inland. These hurricanes combined to cause ~50 billion dollars in damage for the United States (Beven et al., 2019; Stewart & Berg, 2019). Figure 1 shows the tracks and intensities of all Atlantic tropical cyclones in 2018 and also summarizes how the season compares with climatology for named storm numbers, hurricane numbers, major hurricane numbers (Category 3+ on the Saffir-Simpson wind scale), and Accumulated Cyclone Energy (ACE; Bell et al., 2000). The 2018 hurricane season was ~25% above average for named storm numbers, hurricane numbers, and ACE with values of 15, 8, and 133×10^4 kt^2, respectively, but slightly below average for major hurricane numbers with Florence and Michael in this category. Since the season had an ACE above 111×10^4 kt^2 and at least 13 named storms and 7 hurricanes, it met the National Oceanic and Atmospheric Administration (NOAA) definition of an above-normal Atlantic hurricane season (NOAA, 2018a).

Seasonal Atlantic hurricane outlooks show moderate-to-good forecast skill by the start of the peak of the Atlantic hurricane season in early August (Klotzbach et al., 2017). However, the above-normal nature of the 2018 hurricane season was not predicted. The three agencies with the longest record of issuing seasonal outlooks for Atlantic hurricane activity and whose real-time skill was assessed by Klotzbach et al. (2017) all called for a below-normal 2018 Atlantic hurricane season in early August 2018. Table S1 in the supporting information lists the hurricane outlooks issued publicly by these agencies between early December 2017 and early August 2018. In addition, most of the other publicly available hurricane outlooks issued by over 20 university, government, and private weather enterprises between May and early August 2018 also called for either below-normal or near-normal Atlantic hurricane activity in 2018 (Seasonal Hurricane Predictions, 2018). Statistical and dynamical seasonal hurricane outlook models performed similarly with most also decreasing their anticipated seasonal hurricane activity between late May and early August 2018. The main reasons for the below-normal outlooks were the occurrence of anomalously cool waters in the tropical North Atlantic between April and July 2018, and the expectation that weak El Niño conditions would develop by the second half of the hurricane season in September–October, factors that both typically suppress Atlantic hurricane activity (Klotzbach & Bell, 2018; NOAA, 2018b).

a



b

Tropical cyclone parameter	2018 value	1981-2010 climatology value	2018 value as percentage of climatology
Named Storms	15	12.1	124%
Hurricanes	8	6.4	125%
Major Hurricanes	2	2.7	74%
Accumulated Cyclone Energy (ACE)	133	106	125%

Figure 1. Summary of the 2018 Atlantic hurricane season. (a) Tracks and intensities of all Atlantic tropical cyclones in 2018 and (b) the 2018 season compared with climatology for different parameters. Panel (a) is courtesy of the U.S. National Hurricane Center.

Previous failures of Atlantic seasonal hurricane forecasts have been interpreted, in general, in terms of El Niño-Southern Oscillation (ENSO) and/or tropical Atlantic sea surface temperatures (SSTs) and their associated wind patterns not developing/behaving as expected. However, in 2018, most of the statistical and dynamical model ENSO predictions from May/June anticipated correctly the occurrence of neutral ENSO conditions during August–September and a warming to weak El Niño conditions by October. Forecasts

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also anticipated correctly from late May that tropical Atlantic SSTs in the hurricane main development region (MDR), as defined in section 3.1, would be cooler than their 1981–2010 average values during August–September 2018. That said, seasonal hurricane forecasts tended to anticipate tropical Atlantic waters that were cooler than observed due to a somewhat unexpected 0.7 °C warming in tropical Atlantic SST anomalies between June and September 2018. In section 4.3 we show that when the August–September environmental fields that best replicate Atlantic hurricane activity over a 135-year period (Saunders et al., 2017) are applied to 2018, they anticipate a below-normal 2018 hurricane season (as do the other environmental fields that are also well linked to annual Atlantic hurricane activity). The mismatch between the observed and replicated/forecast levels of Atlantic hurricane activity in 2018 clearly reflects the uncertainty inherent in hurricane outlooks.

3. Data and Methods

3.1. Environmental Variables

Figure 2 lists and displays the six environmental fields and their regions that we use in quantifying the explained variance in Atlantic hurricane activity between 1950 and 2017, and in making hindcasts of 2018 hurricane activity. These fields are chosen due to their recognized use in contemporary statistical modeling of seasonal Atlantic hurricane activity. The environmental fields divide into three classes comprising two atmospheric fields, one SST field, and three climate oscillations. In keeping with Saunders et al. (2017), we examine August–September conditions for all fields except for ENSO where we use August-September-October data because NOAA defines ENSO using a 3-month average.

The two atmospheric fields are the anomaly in the low-level zonal trade wind speed, u_T, at 925 hPa over the Caribbean and tropical North Atlantic (Saunders & Lea, 2008; see also Klotzbach, 2011) and the anomaly in zonal vertical wind shear, VWS, defined as the magnitude of the difference in zonal wind speed at 200 and 850 hPa over the Caribbean and western tropical North Atlantic (Sharmila & Walsh, 2017). The SST field examined is the anomaly in the eastern and central hurricane MDR SST (Saunders & Harris, 1997; Saunders & Lea, 2008). The three climate oscillations assessed are the SST component of the Atlantic Meridional Mode (AMM; Vimont & Kossin, 2007; see also Patricola et al., 2014), the Atlantic Multi-decadal Oscillation (AMO; Goldenberg et al., 2001; see also Klotzbach, 2011), and ENSO defined by the Oceanic Niño Index (ONI; Patricola et al., 2014). The physical basis for how each environmental field is linked to seasonal Atlantic hurricane activity is described in the papers referenced above.

3.2. Data Sources

The study employs three types of data: 6 hr best-track Atlantic hurricane data, monthly gridded reanalysis data, and monthly climate index data. These data are used for the 2018 Atlantic hurricane season and for prior Atlantic hurricane seasons between 1950 and 2017.

Best-track Atlantic hurricane data are obtained from the Atlantic HURDAT2 (HURricane DATa second generation) database (Landsea & Franklin, 2013). These data were accessed on 17 May 2019 (2018 season) and on 22 October 2018 (1950–2017 seasons). There were no changes made to the 1950–2017 HURDAT2 data between the time of our two downloads. These data provide 6 hr estimates for the location and intensity of each tropical cyclone throughout its lifetime. HURDAT2 data are used to compute the following annual measures of hurricane activity: the number of named storms, the number of hurricanes, the number of major hurricanes, and the ACE. Annual ACE combines the intensity and duration of all Atlantic named storms for a single season into a single value and is defined as the sum of the squares of the maximum 1-min sustained surface wind speed every 6 hr for all named storms while they are at least of tropical storm intensity (≥34 kt; ≥17.5 m/s) (Bell et al., 2000).

Monthly gridded reanalysis data are obtained from the NCEP/NCAR global reanalysis (Kistler et al., 2001). These data are provided on a 2.5° latitude/longitude grid and are available in near real time. They are used to compute values for the two atmospheric environmental fields and for the SST field. We also examined NOAA Extended Reconstructed SST Version 5 data (Huang et al., 2017) for the SST environmental field, and data from the NOAA 20th Century Global Reanalysis Version 2c (Compo et al., 2011) and the ERA-Interim reanalysis (Dee et al., 2011) for the atmospheric fields. These datasets are used to check whether our findings obtained with the NCEP/NCAR reanalysis are sensitive to the database used. Little a

Environmental field	Region	Reference(s) for prior use
Aug-Sep 925 hPa u_T	7.5-17.5°N, 100-30°W	Saunders and Lea (2008); see also Klotzbach (2011)
Aug-Sep MDR SST	10-20°N, 60-20°W	Saunders and Harris (1997) and Saunders and Lea (2008)
Aug-Sep VWS	10-20°N, 90-40°W	Sharmila and Walsh (2017)
Aug-Sep AMM	21°S-32°N, 74°W-Africa	Vimont and Kossin (2007); see also Patricola et al. (2014)
Aug-Sep AMO	North Atlantic Ocean	Goldenberg et al. (2001); see also Klotzbach (2011)
Aug-Sep-Oct ONI	5°S-5°N, 170-120°W	Patricola et al. (2014)

b

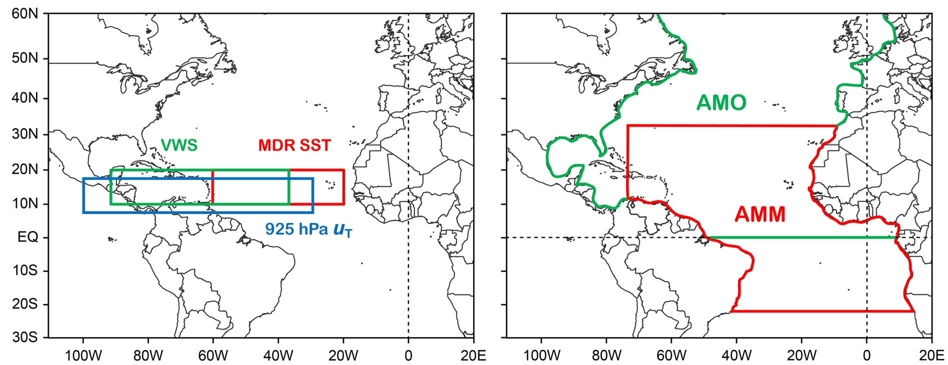

Figure 2. Environmental fields used to assess the explained variance in Atlantic hurricane activity and to make hindcasts of 2018 Atlantic hurricane activity. (a) The six environmental fields and their regions. (b) Location of the five Atlantic environmental fields listed in (a).

sensitivity to dataset was found: For example, the Pearson correlation between the August–September 925 hPa u_T environmental field and ACE had values for 1950–2017 data of 0.68 (NCEP/NCAR reanalysis) and 0.69 (NOAA 20th century reanalysis), and values for 1979–2017 data of 0.71 (NCEP/NCAR reanalysis) and 0.72 (ERA-Interim reanalysis).

Monthly data for the AMM, AMO and ONI climate indices are obtained, respectively, from NOAA/ESRL (2018a), NOAA/ESRL (2018b), and NOAA/CPC (2018). The ONI is computed using Extended Reconstructed SST Version 5 data.

3.3. Methods

We employ the data periods of 1950–2017 and 1979–2017 to assess the variance in annual hurricane activity explained by environmental fields. The second period is included to remove the potential influence of inferior global reanalysis data (especially of upper-atmosphere parameters) that may exist before the development of global satellite monitoring in the late 1970s.

All regressions, including the computation of r^2, are performed using normalized data. This ensures that the requirements of linear regression modeling are met, namely, that observations are drawn from normal distributions and that regression errors are normally distributed with a mean of zero. As the distributions for ACE, the number of hurricanes, and each of the six environmental fields in Figure 2a are all non-normal, we transform each data set to a normalized distribution by using the statistical distributions listed in Table S2. The transform distribution is determined in each case using 1950–2017 data with the 1979–2017 normalized data being a subset of the 1950–2017 normalized data. This method is used because the distribution fits are too noisy when determined only from 1979–2017 data. Normality is assessed using the Anderson-Darling statistical test. To check whether our results are sensitive to the statistical distributions selected to normalize each data set, we also normalized all data sets for the 1950–2017 period by using the cumulative probability method illustrated in Figure 1 of Lloyd-Hughes and Saunders (2002). The PoE values obtained with the two standardization methods agreed to ~1%.

We express the strength of the links between the environmental fields in Figure 2a (both single-predictor and multipredictor) and Atlantic hurricane activity by the percentage of the variance (r^2) in ACE and hurricanes that each field explains for each data period. Hindcasts for 2018 Atlantic hurricane activity are made by using standard linear regression performed on the normalized (transformed) predictor and predictand data for each prior period. The hindcast predictand values are then transformed back to give the final 2018 hindcast values for ACE and hurricanes.

We compute the 2018 standardized anomalies for the environmental fields in Table 1 as follows. For the six individual environmental fields, we standardize by using the field's normalized data for 1981–2010 and the field's normalized value for 2018. For the multifield predictors we standardize by using the normalized field data for 1981–2010 in a multilinear regression to predict standardized ACE values and then standardize the 2018 prediction for ACE to the 1981–2010 predictions for ACE.

We compute hindcast PoE values for the 2018 North Atlantic ACE as follows. The same six-step methodology applies also to hurricanes:

1. Take a single (or multi) predictor linear regression model using transformed 1950–2017 data for the predictor(s) and for ACE.
2. Compute the transformed values for 2018 ACE and each relevant 2018 environmental field.
3. Make a hindcast prediction for 2018 ACE by using the transformed 2018 values obtained in (2) applied to the regression model in (1).
4. Compute the hindcast error for 2018 ACE by taking the difference between the ACE values obtained in (3) and (2).
5. Standardize the hindcast error in (4) by dividing by the standard deviation of the regression model residuals obtained in (1).
6. Compute the probability of exceeding the standardized hindcast error in (5) by recognizing that this value is part of a standard normal cumulative probability distribution.

The influence of geographic climate zone on the strength of the links between the six individual environmental fields in Figure 2a and the Atlantic ACE within that zone is examined for three climate zones: "Tropics" is defined as the region 0–23.5°N, 100–20°W; "subtropics" is defined as the region 23.5–35°N, 100–20°W; and "midlatitudes" is defined as the region 35–50°N, 100–20°W. Storms that form outside a climate zone and later propagate into that zone are considered to contribute to the ACE in that zone when they are located within that zone.

4. Deterministic Modeling of the 2018 Atlantic Hurricane Season

4.1. Performance of Environmental Predictor Fields 1950–2017

The strength of the links between the environmental fields considered here and Atlantic hurricane activity is shown in Table 1 (left part) for the 1950–2017 and 1979–2017 periods. The assessment is made in terms of r^2 against both ACE and hurricane numbers; this is for each of the six individual fields and for the four multifield combinations involving the fields that individually have the highest r^2 for ACE. The analysis shows that August–September environmental fields explain 50–55% of the variance in ACE between 1950 and 2017, increasing to 60–70% of the variance between 1979 and 2017. August–September environmental fields explain slightly less variance for hurricane numbers, with 40–45% of the variance explained between 1950 and 2017, increasing to 50–60% of the variance between 1979 and 2017. The environmental fields that individually perform best for the periods 1950–2017 and 1979–2017 are, respectively, the trade wind speed, u_T, and zonal VWS. In general, the multifield combinations explain slightly more variance in ACE and hurricanes than do the single field predictors.

The nature and robustness of the deterministic links between the key environmental predictor fields in Table 1 and ACE is examined in more detail in Figure 3. This figure displays scatterplots of three August-September fields (925 hPa u_T, MDR SST, and zonal VWS) against ACE for the 1950–2017 and 1979–2017 periods. Large changes are evident in the most likely (deterministic) ACE value as the sign and magnitude of the anomaly in each predictor field changes. However, there is also a sizeable spread of ACE outcomes possible for any given predictor field value. It is this spread of possible outcomes that gives rise to the uncertainty in seasonal hurricane outlooks. The red circles in Figure 3 denote the 2018 environmental field values. The observed 2018 ACE value of 133×10^4 kt^2 is close to the historical upper limit of possible ACE outcomes given the 2018 environmental field values.

Table 1
Key Environmental Fields: Explained Variance in North Atlantic Hurricane Activity, 2018 Anomaly Values, and 2018 Hindcasts for ACE (×10^4 kt^2) and Hurricane Numbers (H)

Environmental field/predictor	Variance explained (r^2) %				2018 standardized anomaly	2018 hindcast values			
	1950–2017		1979–2017			1950–2017 training		1979–2017 training	
	ACE	H	ACE	H		ACE	H	ACE	H
925 hPa u_T and AMM	53	42	59	50	−0.68	60	5	60	5
925 hPa u_T and MDR SST	52	40	57	43	−0.64	61	5	57	5
925 hPa u_T	52	38	55	39	−0.57	62	5	61	5
Zonal VWS and AMM	50	44	66	59	−1.13	47	4	42	4
Zonal VWS and MDR SST	50	42	66	55	−1.18	46	4	42	4
Zonal VWS	44	36	62	52	1.23	47	4	43	4
AMM	33	33	48	48	−0.77	67	5	56	5
MDR SST	22	21	39	34	−0.74	74	5	59	5
AMO	20	21	30	31	0.16	101	7	97	6
ENSO ONI	11	14	23	28	0.54	79	6	76	6

Note. The environmental fields/predictors are ordered by their explained variance for ACE for 1950–2017. August–September values are used for all of the environmental fields/predictors except for ENSO ONI where August-September-October values are used because NOAA defines the ONI to be a 3-month average. All 2018 standardized anomalies are defined with respect to the 1981–2010 climatology. The sign of the 2018 standardized anomaly for the multifield predictors is defined such that a negative value means that the combination is unfavorable for ACE.

4.2. Environmental Predictor Fields in 2018

Table 1 (center part) lists the 2018 standardized anomalies for the six August–September individual fields and for the four August–September multifield combinations. The four individual fields that explain the most long-term hurricane activity (925 hPa u_T, zonal VWS, AMM, and MDR SST) all had 2018 standardized anomalies consistent with well below-normal hurricane activity in 2018. The four multifield predictors (all of which explain at least 50% of the variance in ACE between 1950 and 2017) all had 2018 standardized anomalies between −0.64 and −1.18. These anomalies are also all consistent with a well below-normal 2018 Atlantic hurricane season.

The large mismatch between the observed and anticipated levels of Atlantic hurricane activity in 2018 is particularly striking in Figure 3. These scatter plots show that the 2018 August–September environmental field values all lie well above the historical best fit lines, indicating that the 2018 hurricane season generated considerably more ACE (by a factor of 2) than would have been anticipated given the long-term relationships between each parameter and Atlantic hurricane activity.

The nature of the 2018 anomalies for three August–September environmental fields (925 hPa zonal wind, SST, and 200–850 hPa VWS) is examined in more detail in Figure 4. This figure displays these anomalies spatially across the predictor regions (shown as rectangular green-marked areas) and over the whole North Atlantic. The anomaly signs in the predictor regions are all consistent with below-normal hurricane activity, namely, negative 925 hPa zonal wind anomalies (stronger than normal u_T), negative MDR SST (cooler than normal surface waters), and positive VWS anomalies (stronger than normal VWS). However, the strength of the hurricane-unfavorable conditions during August–September 2018 was not uniform over each predictor region.

4.3. Hindcasts for 2018 ACE and Hurricane Numbers

The observed 2018 values for Atlantic ACE and hurricane numbers were 133 × 10^4 kt^2 and 8, respectively. Deterministic hindcasts for Atlantic hurricane activity in 2018 are displayed in Table 1 (right part). These hindcasts are made by applying the method described in section 3.3 to separate 1950–2017 and 1979–2017 training period data for each of the four multifield combinations (section 4.1) and for each of the six individual fields. The hindcast values are given for ACE and for the number of hurricanes. Every hindcast for both training periods anticipates levels of 2018 hurricane activity that are lower and, in most cases, much lower than that observed. All of the field combinations and individual fields that historically explain the highest variance in ACE and hurricane numbers anticipate an ACE less than 70 × 10^4 kt^2 and 4–5 hurricanes in 2018. These hindcast levels are ~50–60% of those witnessed and, if verified, would have placed the 2018 hurricane season in the lowest one third of years historically for activity. Furthermore, as noted in section 2,

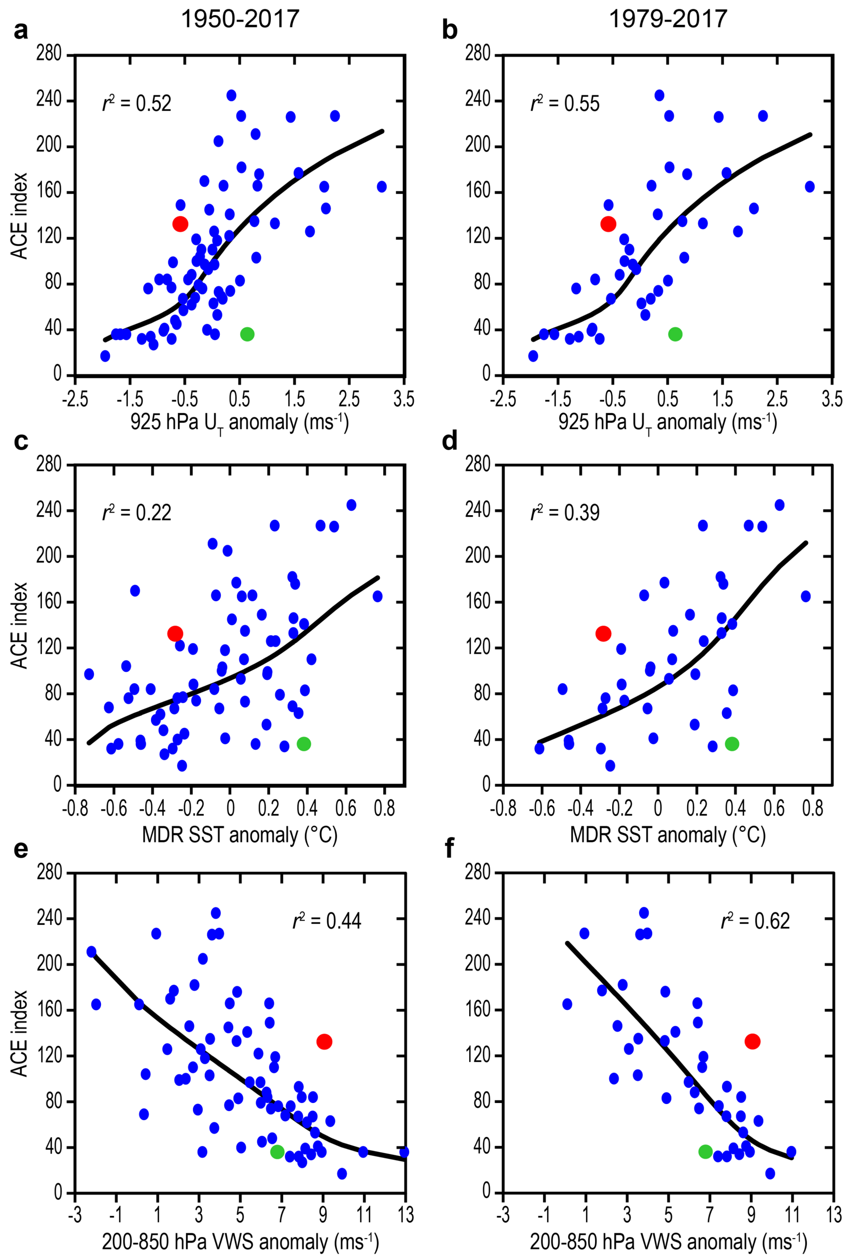

Figure 3. Scatter plots showing the nature and the strength of the links between three key environmental fields in Table 1 and ACE ($\times 10^4$ kt^2). These links are displayed for 1950–2017 data (left column) and for 1979–2017 data (right column). The environmental fields are (a and b) August–September 925 hPa u_T, (c and d) August–September MDR SST, and (e and f) August–September 200–850 hPa zonal VWS. Each panel shows the best fit linear regression line (computed by transforming ACE and each environmental field to normal distributions and then transforming back) and the percentage of the ACE variance that this line explains (r^2). Red circles denote the 2018 values. Green circles denote the 2013 values (mentioned in section 6.1).

several of the public outlooks for the 2018 hurricane season issued between late May and early August 2018 called for hurricane activity similar to that given by these hindcasts (Table S1; Seasonal Hurricane Predictions, 2018).

5. Exceedance Probability Modeling of the 2018 Atlantic Hurricane Season

The large mismatch between the observed and hindcast levels of hurricane activity in 2018 is an extreme example of the uncertainty inherent in deterministic hurricane outlooks. To properly and clearly clarify

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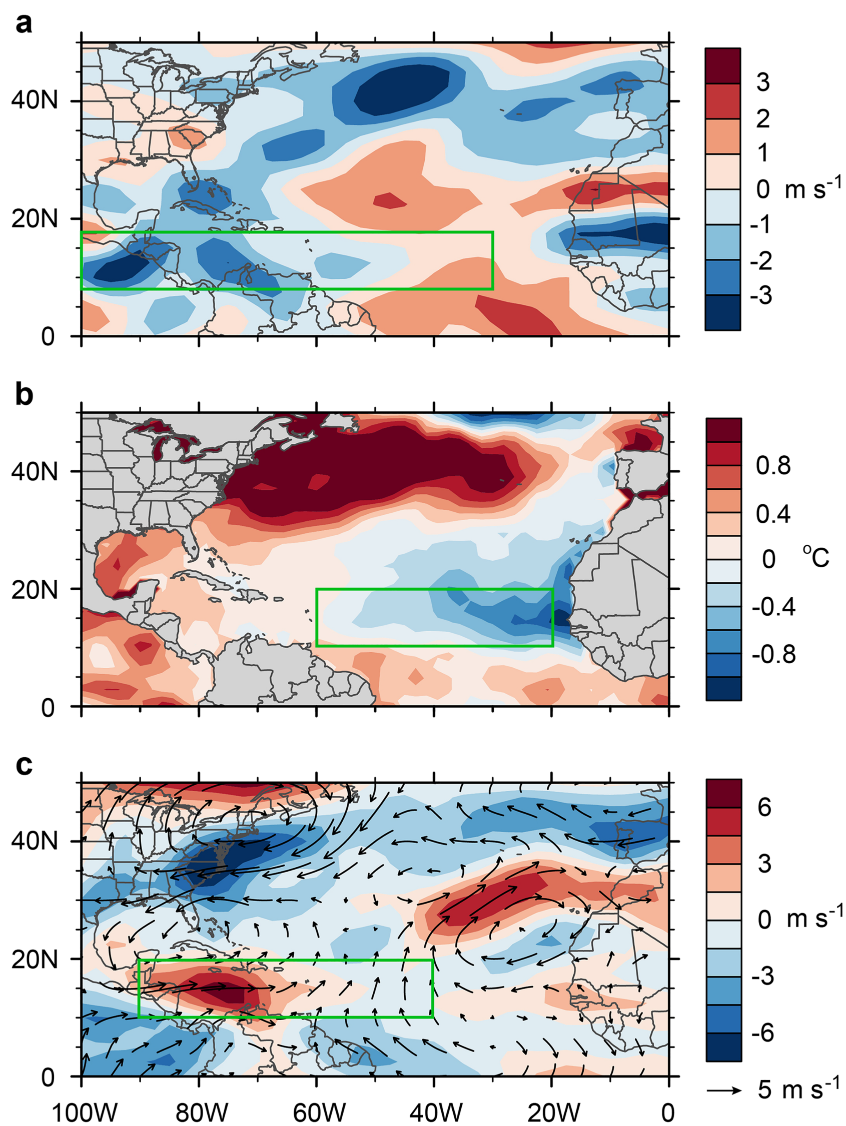

Figure 4. August–September 2018 spatial anomalies in three key environmental fields linked to seasonal Atlantic hurricane activity. The environmental fields are (a) August–September 925 hPa *u*, (b) August–September SST, and (c) August–September 200–850 hPa VWS magnitude and direction. Green rectangles mark the predictor regions (Figure 2a). All anomalies are relative to 1981–2010 climatological values. The VWS anomalies are computed using daily data.

this uncertainty, we propose that hurricane outlooks should also be expressed in terms of probability of exceedance (PoE). PoE is the preferred method used in insurance, finance, and other business sectors to quantify and present the uncertainty in natural hazard outcomes (Grossi & Kunreuther, 2005).

Figure 5 displays hindcast outlooks for the 2018 hurricane season ACE and number of hurricanes in terms of PoE. Each panel shows the observed 2018 hurricane activity values and three sets of PoE data comprising two hindcast PoE curves and the 1950–2017 climatological PoE curve. The hindcast PoE values are computed using the method described in section 3.3 while the climatology PoE values are computed directly from observations. The two hindcast PoE curves employ the multifield combinations described in the Figure 5 caption. These PoE curves represent the range of possible curves given the best-performing environmental fields in Table 1. Each PoE curve specifies the chance that a given hurricane number/activity outcome will be reached based on the multifield predictor combination and historical data period used.

The likelihoods for the observed 2018 values for ACE and number of hurricanes of 133×10^4 kt^2 and 8 being reached can be read easily from Figure 5. These likelihoods are about 5% for the hindcast model output

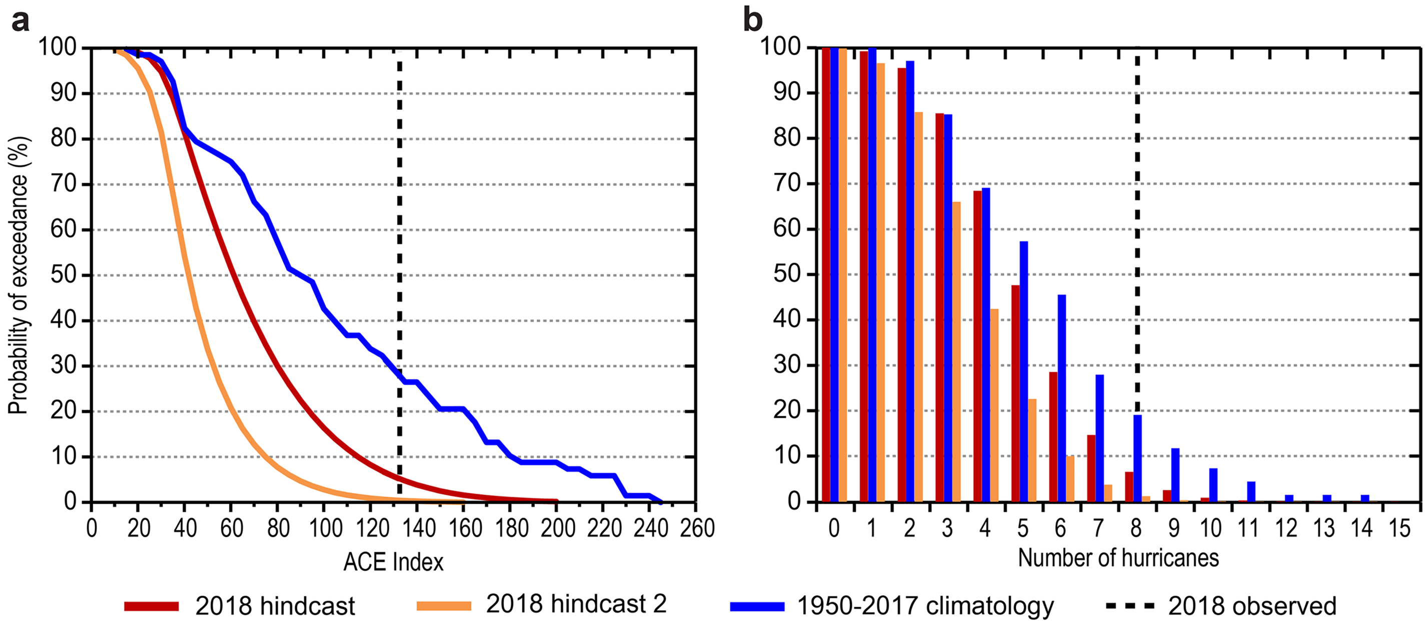

Figure 5. Probability of exceedance (PoE) plots for (a) ACE and (b) the number of hurricanes. Each panel displays three sets of PoE data comprising two hindcasts for 2018 and the 1950–2017 long-term climatology. The hindcasts are made using the August–September 925 hPa u_T and MDR SST regression model (2018 hindcast: red line) and the August–September zonal VWS and MDR SST regression model (2018 hindcast 2: orange line). The 2018 observed values for ACE and number of hurricanes are marked for reference.

displayed in red and about 1% for the hindcast model output shown in orange. Thus, with retrospective knowledge of the key August–September 2018 environmental fields considered here, the statistical odds for the 2018 Atlantic hurricane season being as active as witnessed are very low. Nevertheless, the spread of outcomes based on 68 years of standardized historical training data gives a finite chance for the 2018 Atlantic hurricane season being as active as observed.

A reliability diagram is a transparent way to show the calibration and performance of probability forecasts (Hsu & Murphy, 1986; Weisheimer & Palmer, 2014; Wilks, 2019; World Meteorological Organization, 2002). Figure S1 displays a reliability diagram for the probabilistic ACE hindcasts issued by the August–September 925 hPa u_T and MDR SST two predictor model used in Figure 5a. The methods to compute this diagram are described in Text S1. Figure S1 shows that the probabilistic ACE hindcasts from this predictor model are well calibrated for upper and lower tercile ACE years between 1950 and 2017. This is demonstrated by the reliability curves lying close to the perfect probabilistic reliability line.

6. Factors Contributing to the Unexpectedly Active 2018 Atlantic Hurricane Season

Our statistical models for replicating annual Atlantic hurricane activity find that tropical environmental conditions during August–September 2018 were typical of an Atlantic hurricane season with below-average activity. Given these environmental fields, there is only a ~5% chance that the 2018 Atlantic hurricane season would be as active as observed. With this outcome, it is appropriate to consider why the 2018 Atlantic hurricane season was so active, why there was such a large mismatch between the observed and replicated levels of hurricane activity, and whether this knowledge might further improve the precision of statistical models. We do this first by recognizing in section 6.1 the size and nature of the limitations in our statistical hurricane replication models. We then describe two factors in sections 6.2 and 6.3 that appear responsible for the surprisingly high hurricane activity in 2018. In section 7 we summarize our findings and consider the prospects for reducing the current model limitations based upon these findings.

6.1. Limitations of Statistical Hurricane Outlook Models

The August–September large-scale tropical environmental fields examined here explain 50–55% of the variance in Atlantic basin hurricane activity between 1950 and 2017 (Table 1). Saunders et al. (2017) showed that the August–September 925 hPa u_T field replicates nearly 50% of the variance in ACE across the 135-year period 1878–2012. Thus, the replication of annual Atlantic hurricane activity from tropical environmental fields is strong and stable going back at least 140 years. Despite this success, there remains ~50% of the variance in long-term Atlantic hurricane activity that is not replicated by current statistical outlook models. This level of unexplained variance means that one must expect sizeable discrepancies to occur at times between the observed and replicated levels of hurricane activity. Indeed, such outcomes are evident in Figure 3, which shows that a range of ACE values is possible for a given environmental field value. Another "large error" replicated hurricane season is 2013—denoted by the green circles in Figure 3. ACE was overpredicted by a substantial margin in 2013—the opposite situation to 2018.

The unexplained ACE variance of ~50% will include the effects of unpredictable stochastic events arising from synoptic and mesoscale variability, the effects of extratropical-tropical interactions, and the influence of potentially unknown seasonal environmental factors. Hurricanes Florence and Michael provide examples of unpredictable stochastic events that contributed to the surprising high 2018 ACE total. Florence contributed 30% of the 2018 Atlantic ACE. Most of this ACE was generated after it was unusually steered toward the United States by a strong high pressure ridge when tracking northwestward in the mid-Atlantic near 25°N, 50°W (Stewart & Berg, 2019). This steering flow tracked Florence into an environment conducive to sustained intensification (warm SST and low VWS). Had this unusual steering forcing not occurred, Florence would likely have recurved well to the east of Bermuda as a weaker hurricane and dissipated much earlier. Hurricane Michael became the fourth strongest hurricane to make landfall in the United States with a wind intensity of 140 kt. Michael's exceptional and surprisingly high wind intensity is thought to have been enabled by the coincident occurrence of a midlatitude trough moving through the western Gulf of Mexico states that created a strong outflow channel to Michael's north (Beven et al., 2019) and increased warm air advection, especially to Michael's east (Callaghan, 2019). Had this synoptic event not occurred, Michael's intensity and ACE would likely have been lower.

6.2. Very Active Subtropics

High tropical storm and hurricane activity in the Atlantic subtropics (23.5–35°N, 20–100°W) contributed to the large hindcast error in 2018. The subtropical ACE in 2018 was 86% above the 1981–2010 average (at 78×10^4 kt^2), 187% of the 1981–2010 median, and the 6th highest subtropical ACE since 1979. By analogy with the NOAA definition of a hyperactive Atlantic hurricane season, which is an ACE value above 165% of the 1981–2010 median (NOAA, 2013), the subtropical ACE in 2018 would be classified as hyperactive or very active. In contrast, the tropical ACE in 2018 was 15% below the 1981–2010 average (at 41×10^4 kt^2). Furthermore, 2018 is one of only 2 years during the 40-year period 1979–2018 where the subtropical ACE exceeded the tropical ACE and where the total ACE was above climatology (106×10^4 kt^2).

Figure 6 displays the variation in ACE by geographic climate zone and quantifies how climate zone influences the level of ACE replication by the six environmental fields in Figure 2a. The three climate zones considered are the "tropics," "subtropics," and "midlatitudes," with each defined in section 3.3. Figure 6b shows that the August–September environmental fields used to statistically model Atlantic hurricane activity have notably less skill (by a factor of 2) in replicating ACE in the subtropics than ACE in the tropics. Since the 2018 hurricane season had 90% more ACE in the subtropics than in the tropics, the chance of having a large difference between the observed and replicated levels of hurricane activity in 2018 is higher than would be the case in most other hurricane seasons where the subtropical ACE is either less than or comparable to the tropical ACE. This interpretation agrees with the observational findings within Kossin et al. (2010) and Boudreault et al. (2017), who show that the typical drivers of Atlantic hurricane interannual variability do not explain well the variability in subtropical hurricane activity. Figure 6 and its interpretation are also consistent with the findings reported by Goldenberg and Shapiro (1996) and Kimberlain and Elsner (1998) that higher subtropical storm activity tends to occur when conditions in the tropics are less conducive to hurricane activity.

A feature of the high storm activity in the subtropics in 2018 was the occurrence of six named storms (Chris, Debby, Ernesto, Joyce, Leslie, and Oscar) that originated from subtropical cyclones north of 23.5°N. This is the highest annual total for North Atlantic subtropical-originating named storms since such records began in 1968. These six systems generated 32% of the 2018 Atlantic ACE, a figure that exceeds the ACE climatology contribution from such systems by a factor of 6. The highest individual ACE contribution came from

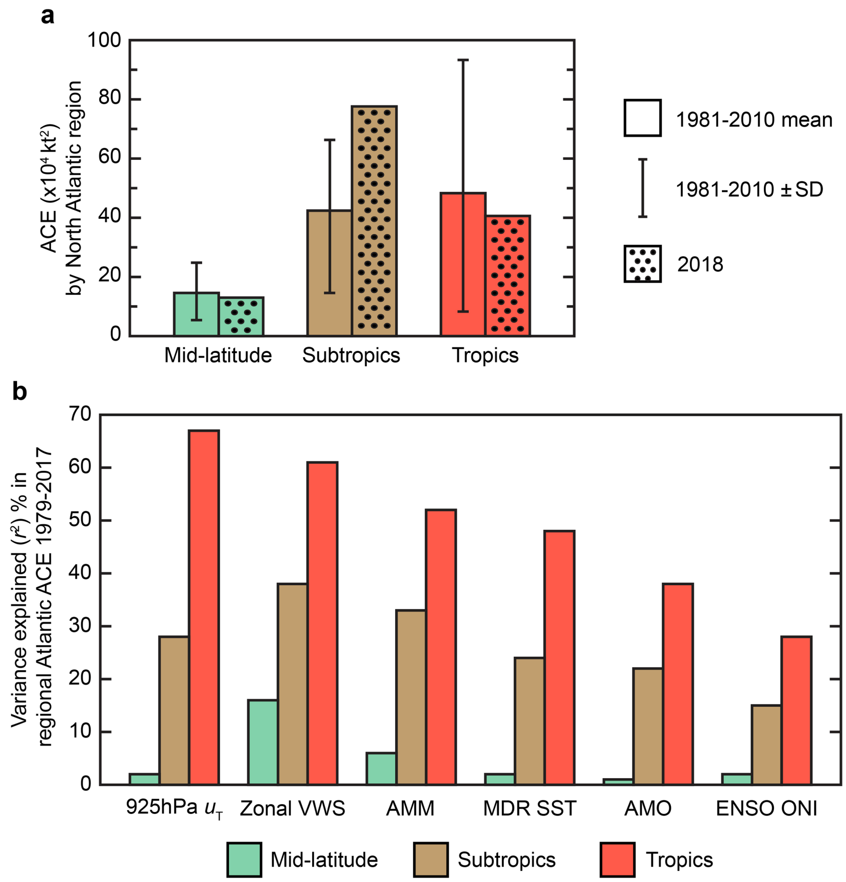

Figure 6. Nature and replication of North Atlantic ACE by geographic climate zone. Panel (a) displays the ACE climatology, ACE standard deviation (SD), and 2018 ACE value for each climate zone. Panel (b) displays the variance in ACE 1979–2017 by climate zone that is explained by each of the six August–September environmental fields considered here. The r^2 values are computed from standardized data.

hurricane Leslie, which persisted for 20 days in the subtropics and contributed 16% of the 2018 ACE. The unusually warm SSTs and low VWS in the western and central subtropical North Atlantic (Figure 4) may have contributed to the large number of subtropical storms and the large subtropical ACE total in 2018. This suggestion agrees with the findings reported by Wang et al. (2019).

6.3. September Hurricane Outbreak

A hurricane outbreak in early September close to the climatological peak of the Atlantic hurricane season also contributed to the large hindcast error in 2018. This outbreak comprised five tropical storms (Florence, Gordon, Helene, Isaac and Joyce) that formed between 1 and 12 September with three of these becoming hurricanes (Florence, Helene, and Isaac). The ACE generated by these five named storms contributed 50% of the total 2018 ACE, with hurricane Florence alone contributing 30% of 2018 ACE. However, as 55% of the ACE generated by the September hurricane outbreak manifested as subtropical ACE, this factor is linked to the factor described in section 6.2. Initial inspection suggests that the early September hurricane outbreak was not associated with the eastward passage of a convectively enhanced phase of the Madden-Julian Oscillation. The outbreak was preceded by a decrease in sea level pressure in the tropical Atlantic and an enhancement of the African monsoon. Perturbations in SST, trade wind speed, and VWS then moved westward from Africa to the Caribbean resulting in the “zonal VWS” environmental field predictor briefly becoming below average around 10 September (figure not shown).

In contrast, August 2018 was notable for a lack of tropical cyclones with only two short-lived named storms (Debby and Ernesto) that contributed just 2% of the 2018 ACE. August 2018 had the second-lowest August ACE since 1997, trailing only 2013.

7. Prospect for Improved Hurricane Outlook Precision

Two factors contributed to the surprising high hurricane activity in 2018. These were high storm and ACE activity in the subtropics and an early September hurricane outbreak. The hyperactive subtropics was the primary factor in our opinion. This activity was poorly anticipated because contemporary statistical models of seasonal Atlantic hurricane activity lack skill in anticipating subtropical ACE compared to tropical ACE.

Recognizing the two factors described in sections 6.2 and 6.3, it is appropriate to assess the prospect for improving the precision of statistical hurricane outlooks based upon this knowledge. At present the influence of these factors is mostly missing in these outlooks. The reasons for this absence are twofold. First, the August–September environmental fields in Table 1 have little skill in anticipating tropical storm activity in the subtropics (Figure 6); the main predictive skill of these fields relates to tropical storm activity in the tropics. Second, the environmental fields in Table 1 lack the ability to diagnose submonthly changes because they relate to average conditions over a 2-month period.

In our opinion it would be challenging for statistical models to anticipate the hurricane outbreak that occurred over 12 days in early September. This event needs further detailed study to determine its cause, but even with this understanding, it would appear unlikely that statistical models could replicate and predict such a time-limited event using large-scale environmental fields. It would be worthwhile to explore whether improved skill may be found for replicating seasonal subtropical storm numbers and subtropical ACE. The separation of subtropical and tropical ACE seasonal components may allow the diagnostic role(s) on subtropical ACE of subtropical and midlatitude Atlantic environmental fields and of the North Atlantic Oscillation to be defined better. Although tropical storms in the subtropics can have erratic tracks and nontropical origins that may limit the seasonal predictability of subtropical ACE, the occurrence in recent years of several major hurricanes in the subtropics suggests that an examination of the predictability of subtropical ACE and of subtropical hurricane and storm numbers is merited.

8. Conclusions and Recommendation

The 2018 North Atlantic hurricane season highlights the large uncertainty that can exist in seasonal hurricane outlooks and the need for robust probabilistic information to better quantify and inform this uncertainty. The August–September large-scale tropical environmental fields that historically explain ~50% of the variance in long-term Atlantic basin hurricane activity all anticipate basin hurricane levels in 2018 that are only 50–60% of that observed. Robust probability of exceedance modeling gives a small (5%) chance of replicating the observed 25% above-average 2018 hurricane activity.

The primary reason for the surprisingly high hurricane activity in 2018 was the unusually high subtropical ACE in 2018. Current statistical models of seasonal Atlantic hurricane activity poorly anticipate subtropical ACE compared to tropical ACE. Hence, the chance of having a large difference between the observed and replicated levels of hurricane activity in 2018 is higher than would be the case in most other hurricane seasons where the subtropical ACE is either less than or comparable to the tropical ACE. Whether hurricane outlook precision for seasons such as 2018 can be improved depends mainly on whether further research finds improved diagnostic and predictive relationships for subtropical ACE.

We recommend that future seasonal hurricane outlooks include robust probability of exceedance information similar in format to our Figure 5. Such probabilistic information would better clarify the uncertainty in hurricane outlooks (based on prior model performance) to the benefit of users. The authors plan to implement this in their hurricane outlooks starting in 2020.

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