SPECIAL
U.S. CLIVAR Hurricanes
COLLECTION

The Impact of the El Niño–Southern Oscillation and Atlantic Meridional Mode on Seasonal Atlantic Tropical Cyclone Activity

Christina M. Patricola and R. Saravanan

Department of Atmospheric Sciences, Texas A&M University, College Station, Texas

Ping Chang

Department of Oceanography, and Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, and Physical Oceanography Laboratory/Qingdao Collaborative Innovation Center of Marine Science and Technology, Ocean University of China, Qingdao, China

(Manuscript received 11 November 2013, in final form 13 March 2014)

ABSTRACT

Atlantic tropical cyclone (TC) activity is influenced by interannual tropical Pacific sea surface temperature (SST) variability characterized by the El Niño–Southern Oscillation (ENSO), as well as interannual-to-decadal variability in the interhemispheric gradient in tropical Atlantic SST characterized by the Atlantic meridional mode (AMM). Individually, the negative AMM phase (cool northern and warm southern tropical Atlantic SST anomalies) and El Niño each inhibit Atlantic TCs, and vice versa. The impact of concurrent strong phases of the ENSO and AMM on Atlantic TC activity is investigated. The response of the atmospheric environment relevant for TCs is evaluated with a genesis potential index.

Composites of observed accumulated cyclone energy (ACE) suggest that ENSO and AMM can amplify or dampen the influence of one another on Atlantic TCs. To support the observational analysis, numerical simulations are performed using a 27-km resolution regional climate model. The control simulation uses observed SST and lateral boundary conditions (LBCs) of 1980–2000, and perturbed experiments are forced with ENSO phases through LBCs and eastern tropical Pacific SST and AMM phases through Atlantic SST.

Simultaneous strong El Niño and strongly positive AMM, as well as strong concurrent La Niña and negative AMM, produce near-average Atlantic ACE suggesting compensation between the two influences, consistent with the observational analysis. Strong La Niña and strongly positive AMM together produce extremely intense Atlantic TC activity, supported largely by above average midtropospheric humidity, while strong El Niño and negative AMM together are not necessary conditions for significantly reduced Atlantic tropical cyclone activity.

1. Introduction

Interannual variability in tropical Pacific sea surface temperature (SST) characterized by the El Niño–Southern Oscillation (ENSO) strongly influences Atlantic tropical cyclone (TC) activity by inducing changes in tropospheric vertical wind shear (Gray 1984; Goldenberg and Shapiro 1996) and upper tropospheric temperatures (Tang and Neelin 2004) in the tropical Atlantic. Atlantic TC activity is also influenced by modes of Atlantic climate variability, including the interannual-to-decadal Atlantic meridional mode (AMM) (Vimont and Kossin 2007; Kossin and Vimont 2007), which describes the meridional gradient between northern and southern tropical Atlantic SST (Chang et al. 1997; Servain et al. 1999; Chiang and Vimont 2004), and the Atlantic multidecadal oscillation (AMO) (Landsea et al. 1999; Goldenberg et al. 2001; Vitart and Anderson 2001), which describes North Atlantic SST variability.

Different phases of the AMO can dampen or amplify the effect of ENSO on Atlantic TC activity on multidecadal time scales (Bell and Chelliah 2006). Similarly ENSO and AMO together provide a more complete

Corresponding author address: Christina M. Patricola, Department of Atmospheric Sciences, Texas A&M University, 3150 TAMU, College Station, TX 77843.
E-mail: cmd58@cornell.edu

DOI: 10.1175/JCLI-D-13-00687.1

explanation of TC variability in the Caribbean region than the individual climate modes do (Klotzbach 2011). On interannual to decadal time scales, the AMM exhibits strong correlations with Atlantic TC activity and explains twice as much variance compared with local SST in the TC development region (Vimont and Kossin 2007). This work focuses on how interferences between interannual tropical Pacific (ENSO) and Atlantic (AMM) climate modes influence tropical cyclone variability in the Atlantic basin.

The objective of this study is to address the following questions. What is the impact of concurrent extreme phases of ENSO and AMM on seasonal Atlantic TC activity, and how do various phases of ENSO and AMM together shape the atmospheric environment for Atlantic TCs? In the next section we review observed relationships between ENSO and Atlantic TC activity, and AMM and Atlantic TC activity, followed by a description of the data and methodology used in this study. The questions posed above are then investigated by analyzing composites of observed Atlantic TC activity according to ENSO and AMM phases. We also evaluate Atlantic TC activity during rare extreme events that are conceivably absent from the data record due to its brevity by forcing a regional climate model with constructed pairs of strong ENSO and AMM phases.

2. Background

Proper guidance for informed seasonal and climate change projections of Atlantic tropical cyclone activity relies on a solid understanding of how prominent modes of climate variability influence TC activity; one such dominant interannual mode in the tropical Pacific, the El Niño–Southern Oscillation, has been widely studied in the context of Atlantic TC variability. Tropical Pacific SST variations associated with ENSO drive changes in the upper tropospheric circulation of the tropical Atlantic through the Walker circulation (Arkin 1982). During El Niño, warmer than average eastern tropical Pacific SST suppresses Atlantic TCs by shifting convection in the tropical Pacific eastward and enhancing upper tropospheric westerly winds and vertical wind shear over the tropical Atlantic (Gray 1984; Goldenberg and Shapiro 1996; Zhu et al. 2012). High values of tropospheric vertical wind shear suppress tropical cyclones (Tuleya and Kurihara 1981; Frank and Ritchie 2001; Wong and Chan 2004), with a threshold of about 7.5–10 $\mathrm{m\,s^{-1}}$ above which TCs are largely inhibited (Zehr 1992; DeMaria et al. 1993). El Niño also inhibits Atlantic TC activity through warm upper tropospheric temperature anomalies (Tang and Neelin 2004). Likewise, cool eastern tropical Pacific SST anomalies during La Niña support strong Atlantic TC activity through reduced vertical wind shear and cooler than average upper tropospheric temperatures in the tropical Atlantic.

ENSO has a profound influence on Atlantic TC landfall over the United States, with a probability of one or more major hurricanes striking the U.S. coast of 23% during El Niño compared to 63% during La Niña, based on the 1900–97 period (Bove et al. 1998). Similarly, U.S. hurricane damage is 20 times greater during La Niña than El Niño years (Pielke and Landsea 1999), and during the 1900–2005 period La Niña significantly increased the probability of hurricanes making landfall on the U.S. East Coast, with minimal changes in landfall frequency along the Gulf of Mexico or Florida (Smith et al. 2007). Owing to the relatively small sample size (about a century) of the data, it is possible for these estimates to change as the record of ENSO and TC activity grows.

Along with interannual variations in tropical Pacific SST, interannual-to-multidecadal Atlantic SST variability strongly affects Atlantic TCs, with warmer North Atlantic SST supporting enhanced TC activity (Emanuel 2005; Webster et al. 2005; Vimont and Kossin 2007; Klotzbach and Gray 2008) through changes in the local boundary layer and tropospheric vertical wind shear in the Atlantic main development region (MDR) (Landsea et al. 1999; Goldenberg et al. 2001; Vitart and Anderson 2001). Two prominent modes of climate variability expressed through Atlantic SST include 1) the Atlantic multidecadal oscillation, which describes multidecadal North Atlantic SST variations and 2) the Atlantic meridional mode (Chiang and Vimont 2004), or the "dipole mode" (Chang et al. 1997; Servain et al. 1999), which characterizes interannual to decadal variations in the cross-equatorial gradient between Northern and Southern Hemisphere tropical Atlantic SST. Both the AMO and AMM encompass the Atlantic main development region; in addition, the AMO includes the remote subtropical and midlatitude North Atlantic, while the AMM includes the remote southern tropical Atlantic. The AMM is a coupled ocean–atmosphere mode that can be generated by external forcings such as ENSO and the North Atlantic Oscillation and is supported by a positive wind–evaporation–SST (WES) feedback (Curtis and Hastenrath 1995; Nobre and Shukla 1996; Chang et al. 1997; Xie and Tanimoto 1998; Giannini et al. 2000).

Recently, Vimont and Kossin (2007) demonstrated a strong positive relationship on both the interannual and decadal time scales between Atlantic TC activity and tropical Atlantic SST characterized by the AMM. Several conclusions arise from that study with significant bearing on the way we think about Atlantic TC variability: 1) Atlantic TC activity is correlated more strongly with the AMM than with the AMO, 2) the AMM explains twice as much variance in Atlantic TC activity compared with local SST in the MDR/northern tropical Atlantic, and 3) the AMM influences several environmental factors that cooperate in their impact on Atlantic TCs, including thermodynamic (static stability) and dynamic (vertical wind shear and low-level vorticity) variables. Modeling experiments with prescribed SST forcings provide evidence that the vertical wind shear and air temperature and moisture anomalies correlated with the AMM in observations are indeed caused by the AMM (Smirnov and Vimont 2011). The AMM is also positively correlated with the frequency of African easterly waves (Belanger et al. 2014), which may further contribute to its influence on Atlantic TC activity through the number of TC "seeds" (Avila 1991; Landsea 1993). These studies suggest that the conventional perspective of considering North Atlantic SST and/or local SST in the northern tropical Atlantic (i.e., the MDR) should be refined to focus on the cross-equatorial SST gradient, which depends on both northern and southern tropical Atlantic SST, and that the AMM may be more useful than the AMO in understanding the Atlantic's influence on tropical cyclones on both interannual to decadal time scales; for these reasons we focus on the AMM, rather than the AMO, in this study.

The importance of both tropical Atlantic and Pacific SST variability in controlling Atlantic TC activity spurs the questions: what is the impact of concurrent phases of ENSO and AMM on seasonal Atlantic TC activity, and how do ENSO and AMM together shape the atmospheric environment for Atlantic TCs? Bell and Chelliah (2006) demonstrated that the AMO can dampen or amplify ENSO's influence during hurricane seasons and suggest that both modes together offer a more comprehensive understanding of seasonal Atlantic TC variability compared to considering only ENSO. Similarly, ENSO and AMO in combination provide a more complete explanation of Caribbean TC variability, with La Niña and positive AMO together producing 14 times more major hurricanes than El Niño with negative AMO during the 1900–2008 period (Klotzbach 2011). Both aforementioned studies motivate applying this perspective to understanding seasonal TC activity in the entire North Atlantic.

Of additional interest is how Atlantic tropical cyclone activity responds to *extreme* AMM and ENSO phases, cases which may be missing from the short observational record simply because they are relatively rare. The importance of this question is highlighted by the most active Atlantic hurricane season on record, the destructive season of 2005, which occurred during an extremely positive AMM and neutral ENSO. Although predictions released in August 2005 by both the National Oceanic and Atmospheric Administration (Bell et al. 2005) and the team of W. M. Gray at Colorado State University (Gray and Klotzbach 2005) called for one of the most active hurricane seasons on record, both underpredicted the number of tropical storms and hurricanes. In addition, the midseason forecast by NOAA predicted a seasonal accumulated cyclone energy (ACE) (Bell et al. 2000), which is defined as the sum of the squares of the 6-hourly maximum sustained wind speed throughout the life of a tropical cyclone, of 158–236 ($\times 10^4$ kt^2) (180%–270% of the median), noting that the primary uncertainty was not whether the season would be above normal, but by how much; the observed ACE exceeded the upper range of the prediction at 250 ($\times 10^4$ kt^2). Understanding how Atlantic TC activity responds to extreme tropical climate variability by using model simulations to fill gaps in the data record, as discussed in section 6, can help improve challenging forecasts like that of the 2005 Atlantic hurricane season for which there are few, if any, similar observed cases.

While this study focuses on the influence of phases of AMM and ENSO on Atlantic TC activity, we emphasize the significance of factors other than Atlantic and Pacific SST variability in shaping Atlantic hurricane seasons. For example, despite similar favorable tropical Pacific and Atlantic SST conditions (positive AMM and neutral ENSO) during the 2005 and 2013 Atlantic hurricane seasons, there was a stark difference in the TC activity between the two, with an extremely high ACE of 250 in 2005, but a well below average ACE of about 35 in 2013. The inactive 2013 Atlantic hurricane season, having been linked to anomalously dry conditions in the midtroposphere, midtropospheric subsidence, and a stronger-than-normal trade wind inversion (Klotzbach and Gray 2013), highlights the importance of factors besides AMM and ENSO.

3. Data and methodology

The following subsections describe the observational datasets, climate indices, regional model and simulations, and diagnostic tools that are used in this study.

a. Observational data and climate indices

Observations of seasonal Atlantic accumulated cyclone energy and tropical cyclone, hurricane, and major hurricane frequency are from the revised Hurricane Database (HURDAT2) (Landsea and Franklin 2013), which is updated from HURDAT (Landsea et al. 2004). The HURDAT2 contains information from the "best tracks" of the National Hurricane Center (NHC), a component of the National Centers for Environmental Prediction (NCEP), including 6-hourly tropical and subtropical cyclone intensity, central pressure, position, and size from 1851 to present for the Atlantic and eastern North Pacific basins. Data are available from the Atlantic Oceanographic and Meteorological Laboratory (AOML)/National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD) and from the NHC.

The Atlantic meridional mode is defined as the leading mode of the maximum covariance analysis (MCA) applied to SST and the 10-m wind vector in the tropical Atlantic (21°S–32°N, 74°W–15°E) with a measure of ENSO variability removed as in Chiang and Vimont (2004). For a detailed description of the procedure by which the AMM is calculated, we refer the reader to Chiang and Vimont (2004). The AMM index used in this study is the time series produced by projecting SST from the NCEP–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996) onto the spatial structure of the MCA mode 1, and is calculated by D. J. Vimont at the University of Wisconsin–Madison and provided by the NOAA Earth System Research Laboratory (ESRL).

ENSO variability is represented by the Niño-3.4 index of the NOAA Climate Prediction Center (CPC), calculated as the area average of eastern-central equatorial Pacific (5°S–5°N, 170°–120°W) monthly SST from the Extended Reconstructed Sea Surface Temperature (ERSST.v3b) dataset (Smith et al. 2008). We express the Niño-3.4 index in terms of anomalies by subtracting the 1950–79 monthly climatology from the Niño-3.4 index. The results here are insensitive to the chosen base period since our focus is primarily on percentiles of the index.

b. *Regional climate model and simulations*

Numerical experiments designed to augment the observational analysis are conducted with the Weather Research and Forecasting Model (WRF) (Skamarock et al. 2008) version 3.3, which is developed and maintained by NCAR. WRF is a nonhydrostatic terrain-following model, and the following physical parameterizations [described in chapter 8 of Skamarock et al. (2008)] are used: the Kain–Fritsch cumulus, Lin et al. microphysics, the Rapid Radiative Transfer Model for general circulation models (RRTMG) longwave radiation, Goddard shortwave radiation, Yonsei University (YSU) planetary boundary layer using a Monin–Obukhov surface scheme, and the Noah land surface model. WRF is configured with a horizontal resolution of 27 km and 28 levels in the vertical reaching to 50 hPa on a domain (Fig. 1) covering the Atlantic sector. The model time step is 90 s, and output is saved every 6 h.

Initial and lateral boundary conditions are prescribed from the 6-hourly 2.5° × 2.5° NCEP–U.S. Department of Energy (DOE) Atmospheric Model Intercomparison Project II (AMIP-II) Reanalysis (NCEP-2) (Kanamitsu et al. 2002). SST and sea ice are based on the monthly 1.0° × 1.0° Hadley Centre Global Sea Ice and Sea Surface Temperature dataset (HadISST) (Rayner et al. 2003).

The 21-yr control integration (Table 1) is initialized on 15 January 1980 and run through 31 December 2000, and is named ''year''-e1 corresponding to each of 21 years. Additional simulations for the 1987 (1987-e2 and 1987-e3) and 1999 (1999-e2 and 1999-e3) Atlantic hurricane seasons are run by initializing the model with NCEP-2 during March of the corresponding year (Table 1). For example, the initial conditions of the 1987-e2 and 1987-e3 simulations are taken from NCEP-2 on 29 and 30 March 1987, respectively. The first month of each simulation is disregarded as model spinup.

Much of the control simulation setup follows the protocol of the coordinated experiments of the U.S. Climate Variability and Predictability Program (CLIVAR) Hurricane Working Group, specifically the ''interannual'' experiment (U.S. CLIVAR 2011). This includes the SST and sea ice forcings, annually updating observed greenhouse gas forcings (e.g., CO_2, CH_4, N_2O, CFC-11, and CFC-12), and integration period.

Four perturbed sets of experiments (Table 1) are conducted to investigate the role of extreme ENSO and AMM phases on Atlantic TC activity. ENSO forcing is prescribed through Pacific SST and, since the western domain edge transects the eastern Pacific (Fig. 1), the lateral boundary conditions (LBCs), while prescribed Atlantic SST represents the AMM forcing. The forcings for each strong climate mode phase are based on an observed case when the August–October (ASO) averaged index representing that phase was less than the 15th or exceeded the 85th percentile over the ASO averaged 1950–2012 period. ENSO is represented by the Niño-3.4 index and AMM by the AMM index as described in section 3a. The ASO average is chosen since it is the peak of the Atlantic hurricane season.

By designing the experiments this way, Pacific SST and LBCs of 1987 and 1999 are chosen to represent a strong El Niño and La Niña, respectively, while strongly positive, moderately positive, neutral, and strongly negative AMM are represented by Atlantic SST of 2005, 1999, 1987, and 1984, respectively. Experiments are named by the following convention: ''[year of ENSO case]_[year of AMM case]Atl-e[ensemble number].'' For example, the first ensemble member of the strong La Niña and strongly positive AMM experiment is called ''1999_2005Atl-e1.'' Initial conditions for each

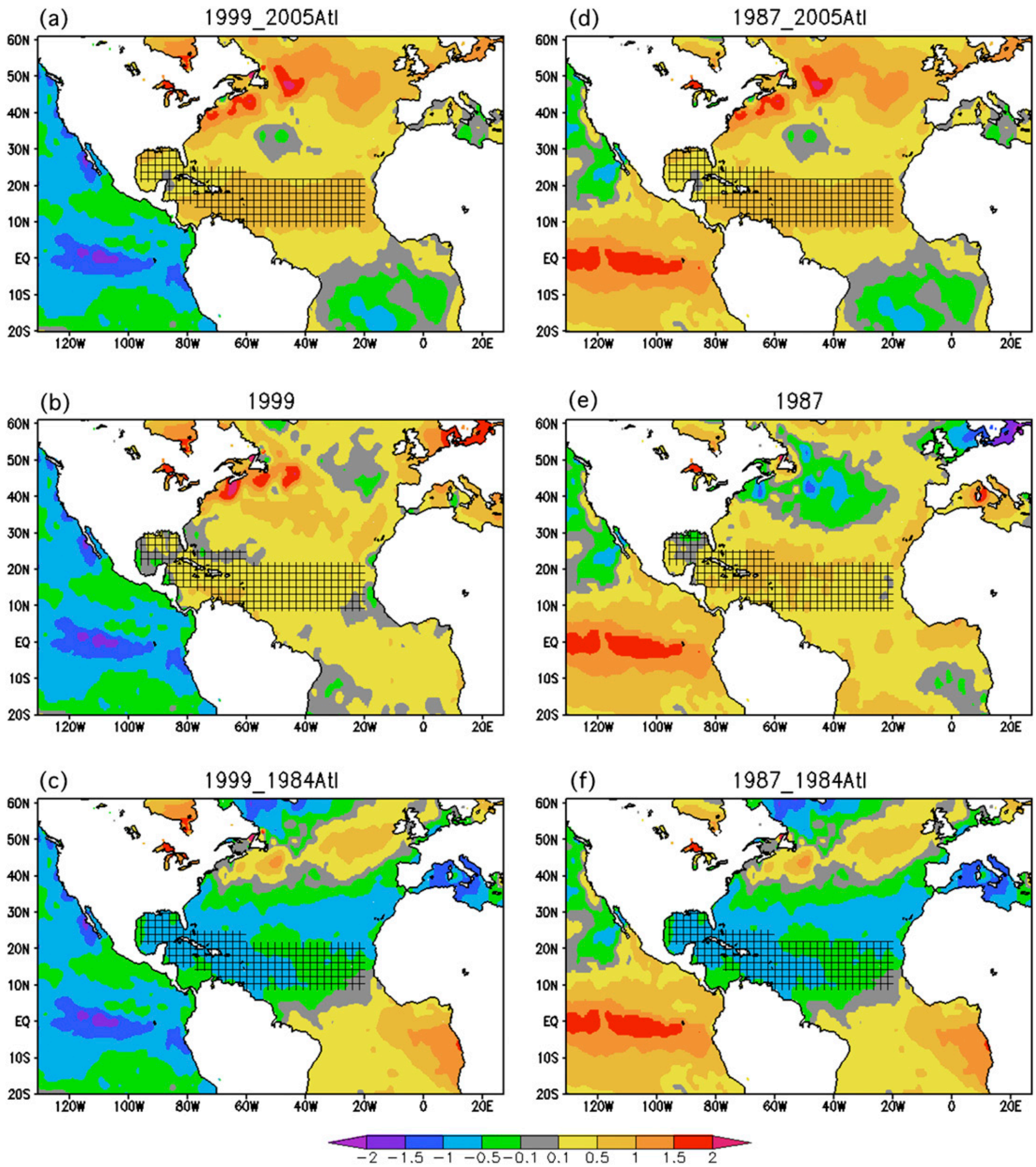

FIG. 1. Prescribed SST (K) forcing averaged over August–October (ASO), as a departure from the ASO 1980–2000 mean, for the (a) 1999_2005Atl, (b) 1999, (c) 1999_1984Atl, (d) 1987_2005Atl, (e) 1987, and (f) 1987_1984Atl simulations on the regional model domain. Land is white, and the main development region and Gulf of Mexico are in black hatching.

experiment are taken from either the model state of the control simulation or reanalysis, as in Table 1, and experiments are run through one hurricane season, terminating on 1 December. Throughout the analysis, when an ensemble-averaged quantity is shown, that quantity is similar among the individual ensemble members unless otherwise noted.

The SST forcings prescribed in the regional climate model (RCM) simulations are shown in Fig. 1, averaged over ASO. The relatively cool eastern tropical Pacific SST of 1999 is prescribed in simulations forced with strong La Niña conditions (Figs. 1a–c), while the warmer than average eastern tropical Pacific SST of 1987 is prescribed in simulations forced with a strong El Niño (Figs. 1d–f). A strongly positive AMM is represented by the above average northern and below average southern tropical Atlantic SST of 2005 (Figs. 1a,d), and a strongly negative AMM is forced through the below average northern and above average southern tropical Atlantic SST of 1984 (Figs. 1c,f).

TABLE 1. Regional climate model simulations designed to investigate the response in Atlantic tropical cyclone activity to forcing characteristic of ENSO (column 2) and AMM (column 3).

Simulation	Pacific SST and LBC (ENSO forcing)	Atlantic SST (AMM forcing)	Initial condition (NCEP-2, unless otherwise stated)
"year"-e1, for years 1980–2000	1980–2000/ variable	1980–2000/ variable	15 Jan 1980
1987_1984Atl-e1 through -e3	1987/ El Niño (strong)	1984/ negative (strong)	29 Mar 1987 (model state of 1987-e1), 29 Mar 1987, 30 Mar 1987
1987-e2 and -e3 (control simulation includes 1987-e1)	1987/ El Niño (strong)	1987/ neutral	29 Mar 1987, 30 Mar 1987
1987_2005Atl-e1 through -e3	1987/ El Niño (strong)	2005/ positive (strong)	29 Mar 1987 (model state of 1987-e1), 29 Mar 1987, 30 Mar 1987
1999_1984Atl-e1 through -e3	1999/ La Niña (strong)	1984/ negative (strong)	26 Mar 1999 (model state of 1999-e1), 26 Mar 1999, 27 Mar 1999
1999-e2 and -e3 (control simulation includes 1999-e1)	1999/ La Niña (strong)	1999/ positive (moderate)	26 Mar 1999, 27 Mar 1999
1999_2005Atl-e1 through -e4	1999/ La Niña (strong)	2005/ positive (strong)	26 Mar 1999 (model state of 1999-e1), 26 Mar 1999, 27Mar 1999, 28 Mar 1999

We note that an inconsistency between LBCs and SST is imposed in the model experiments that use prescribed SST forcings characteristic of the AMM. This prevents the atmospheric response to the SST forcing from propagating globally; however, the local response in Atlantic TCs is captured by the experimental design. As discussed in the following sections, the response in TC activity to AMM and ENSO in the model simulations is similar to that in observations, supporting the validity of the experimental design.

The observational record of Atlantic tropical cyclone activity is relatively short, so it is conceivable that the data record does not include rare extreme events that have yet to be observed. Forcing the model with constructed pairs of extreme phases of ENSO and AMM allows us to evaluate potential gaps in the data record. As we force the model with these extreme combinations of ENSO and AMM, we note that central-eastern tropical Pacific SST can be influenced by North Atlantic SST (Wang et al. 2011); in addition, Atlantic SST is not independent of the Pacific and is influenced by ENSO, particularly in the spring (Enfield and Mayer 1997; Klein et al. 1999; Saravanan and Chang 2000; Mo and Häkkinen 2001; Chang et al. 2006). Northern tropical Atlantic SST may also be affected by the North Atlantic Oscillation (Mo and Häkkinen 2001; Czaja et al. 2002), the AMO (Vimont and Kossin 2007), anthropogenic warming, and sulfate and volcanic aerosols (Mann and Emanuel 2006; Dunstone et al. 2013). Therefore, while this may lead to some tendency for preferred ENSO–AMM combinations, it does not preclude the occurrence of each combination. In fact, each ENSO–AMM pair was observed during at least three Atlantic hurricane seasons from 1950 to 2012. This demonstrates that our proposed question is not contrived and further supports the validity of testing each ENSO–AMM combination.

c. Genesis potential index

The response in environmental conditions relevant for Atlantic TC activity in association with phases of ENSO and AMM is assessed using the tropical cyclone genesis potential index (GPI) developed by Emanuel and Nolan (2004). The GPI, which builds upon the TC genesis index of Gray (1979), is defined as

$$\mathrm{GPI} = |10^5\eta|^{3/2}\left(\frac{H}{50}\right)^3\left(\frac{V_{\mathrm{pot}}}{70}\right)^3(1+0.1V_{\mathrm{shear}})^{-2}, \qquad (1)$$

where η (s^{-1}) is absolute vorticity at 850 hPa; H (%) is relative humidity at 600 hPa; V_{pot} ($\mathrm{m\,s}^{-1}$) is potential intensity (Emanuel 1995; Bister and Emanuel 1998; Bister and Emanuel 2002), which is a function of SST, sea level pressure, and vertical profiles of atmospheric temperature and specific humidity; and V_{shear} ($\mathrm{m\,s}^{-1}$) is the magnitude of vertical wind shear between 850 and 200 hPa. The GPI is computed from monthly averaged quantities.

To assess the utility of the GPI in understanding environmental conditions important for TC activity, we compare the correlation between various measures of observed seasonal Atlantic TC activity from HURDAT2 and reanalyzed GPI for the 1950–2011 period. GPI is computed from the NCEP–NCAR reanalysis (Kalnay et al. 1996) and averaged over ASO and the MDR (9°–21.5°N, 80°–20°W). The correlations (R) between seasonal reanalyzed GPI and observed number of TCs, number of hurricanes, and ACE are 0.38, 0.56, and 0.60, respectively. These correlations suggest that the GPI is a reasonable measure to better understand several of the atmospheric conditions that support TC activity as measured by ACE. (We note that, as expected with any diagnostic, GPI does not provide a full explanation of ACE variability.)

4. Influence of ENSO and AMM on Atlantic tropical cyclone activity: Observations

Investigation of the influence of concurrent phases of ENSO and AMM on Atlantic TC activity begins with an analysis of observed seasonal Atlantic accumulated cyclone energy from HURDAT2 (Landsea and Franklin 2013). Figure 2a shows the deviation from the 1950–2012 mean in observed seasonal Atlantic ACE as a function of the percentile of the corresponding observed ASO averaged AMM and Niño-3.4 indices. The ASO average is chosen for the AMM and Niño-3.4 indices since it is the peak of the Atlantic hurricane season. It is clear from Fig. 2a that a large portion of interannual variability in Atlantic tropical cyclone activity is explained by each AMM and ENSO individually, as has been demonstrated in previous studies (e.g., Gray 1984; Goldenberg and Shapiro 1996; Vimont and Kossin 2007); in addition, it is apparent that considering both AMM and ENSO together provides a more complete explanation of seasonal Atlantic ACE than considering the role of either climate mode alone, with the most active seasons tending to occur during La Niña and/or positive AMM, and the least active seasons tending to occur during El Niño and/or negative AMM. Therefore, we create composites of Atlantic ACE according to the ASO averaged AMM and Niño-3.4 indices (Fig. 2b), with the negative and positive phase defined by the 0th–25th and 75th–100th percentiles, respectively, of the ASO average of those indices as denoted by the dashed black lines in Fig. 2a. (The 25th and 75th percentiles of the ASO averaged Niño-3.4 index for the 1950–2012 period are −0.37 and 0.81, respectively. The 25th and 75th percentiles of the ASO averaged AMM index for the 1950–2012 period are −0.96 and 1.49, respectively.) While we focus on the influence of the AMM and ENSO, we note that a portion of variability in seasonal Atlantic ACE is related to other factors [e.g., upper tropospheric temperature variations unrelated to ENSO or AMM, African easterly waves, Saharan dust (Evan et al. 2006), and internal variability], as evident in Fig. 2a.

The composites of observed Atlantic ACE show that there is vital information to be gained by accounting for both ENSO and AMM together (Fig. 2b). On average, the most active Atlantic TC seasons occur during a positive AMM and La Niña together, with ACE of 181, which is 73% more than the 1950–2012 mean of 105. The observed mean ACE during positive AMM and La Niña

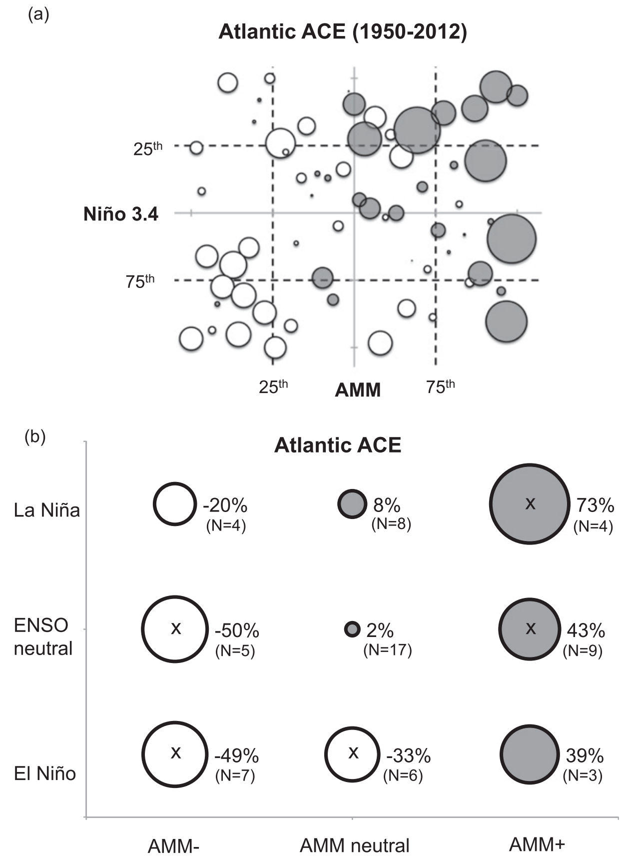

FIG. 2. (a) Deviation from the 1950–2012 mean in observed seasonal Atlantic accumulated cyclone energy (ACE) (10^4 kt^2) from HURDAT2, with the percentile of the observed ASO averaged AMM and Niño-3.4 indices. Deviation in ACE is proportional to the diameter of the circle, with positive shaded gray and negative shaded white. The gray axes represent the 50th percentiles, and the black dashed lines represent the 25th and 75th percentiles, of the ASO averaged AMM and Niño-3.4 indices from 1950 to 2012. (b) Average deviation from the 1950–2012 mean (105×10^4 kt^2) in observed seasonal Atlantic ACE (percent) from HURDAT2 for composites according to the ASO averaged AMM and Niño-3.4 indices. A negative and positive phase is defined by the 0–25th and 75th–100th percentiles, respectively, of the ASO averaged AMM and Niño-3.4 indices during the 1950–2012 period (denoted by the black dashed lines in Fig. 2a). Deviation in ACE is proportional to the diameter of the circle (positive shaded gray) and listed to its right, and the number of occurrences (N) for each ENSO–AMM pair is in parentheses. A mark inside the circle denotes the mean ACE for the given AMM–ENSO pair that is significantly (10% level) different from the mean ACE for the set of all cases not characterized by that AMM–ENSO pair according to a Student's t test. The t test is one-tailed, except for AMM–ENSO pairs with destructive influences on Atlantic tropical cyclones (i.e., positive AMM with positive ENSO, or negative AMM with negative ENSO).

together is significantly (10% level) greater than the mean ACE during the set of all other cases. In addition, concurrent positive AMM and La Niña generally support the greatest number of Atlantic hurricanes (Fig. 3a) and major hurricanes (Fig. 3b) per season. There were

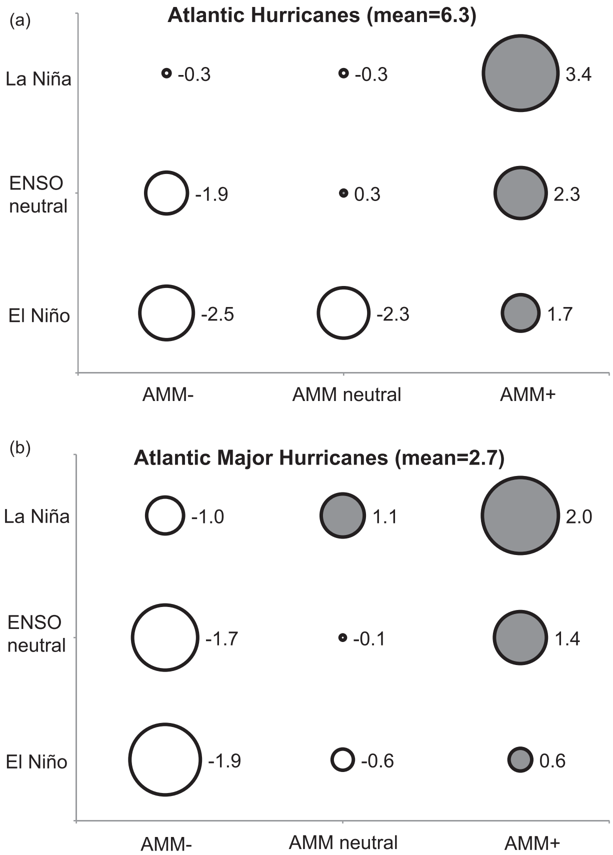

FIG. 3. Average deviation from the 1950–2012 mean in observed number of Atlantic (a) hurricanes and (b) major (category 3, 4, and 5) hurricanes from HURDAT2 for composites according to ASO averaged AMM and Niño-3.4 indices, defined as in Fig. 2b. Deviation is proportional to the diameter of the circle (positive shaded gray) and listed to its right. The 1950–2012 mean is in parentheses.

over 5.5 times more major Atlantic hurricanes per season observed during positive AMM with La Niña compared to concurrent negative AMM and El Niño in the 1950–2012 period, a result that is analogous to the relationship between the number of major hurricanes impacting the Caribbean with AMO and ENSO (Klotzbach 2011). The number of hurricanes that made landfall in the United States during 1950–2012 is also above average during positive AMM with La Niña, although the greatest anomaly occurs during positive AMM with El Niño (not shown). This may be due to the small sample size of a relatively rare event (in comparison to number of Atlantic hurricanes), or differences in preferred TC tracks due to large-scale circulation patterns associated with ENSO and AMM.

The composites of Atlantic ACE also reveal that El Niño alone is not a sufficient condition for weaker than average Atlantic tropical cyclone activity: in fact, when paired with a positive AMM the seasonal activity is on average 39% greater than the mean (Fig. 2b), and the number of Atlantic hurricanes and major hurricanes is greater than the mean (Fig. 3). (We note that the sample sizes for the observationally based composites are generally small, with as few as three observed cases for an AMM and ENSO pair, which motivates the modeling experiments discussed in section 6.) Similarly, La Niña and a negative AMM together support marginally below average (20% less than the mean) Atlantic ACE, suggesting that phases of ENSO and AMM that individually oppose each other in their influence on Atlantic TCs together have a compensating effect. The mean Atlantic ACE during concurrent El Niño and positive AMM, as well as during concurrent La Niña and negative AMM, is not significantly different from the mean ACE during the set of all other ENSO and AMM cases (Fig. 2b). The observational analysis indicates that AMM and ENSO are both primary influences on Atlantic TCs; that is, the AMM does not act as a secondary influence to modulate the impact of ENSO.

Another interesting result from the composites of observed Atlantic ACE is that the weakest Atlantic TC seasons generally do not require the most TC-inhibiting ENSO and AMM conditions together, that is, concurrent El Niño and negative AMM. Atlantic ACE is nearly the same (50% less than the mean) for both negative AMM with El Niño and negative AMM with neutral ENSO (Fig. 2b), and the Atlantic ACE during each of these ENSO and AMM pairs is significantly (10% level) less than the ACE during the set of all cases not characterized by that ENSO and AMM pair. The response in number of Atlantic hurricanes and major hurricanes is similar (Fig. 3), with relatively little difference during negative AMM with either El Niño or neutral ENSO. This suggests that the environmental conditions for TCs are sufficiently poor during concurrent negative AMM and neutral ENSO to effectively reduce Atlantic TC activity.

Although many of the results based on observed Atlantic TC activity presented in this section are statistically significant, the relatively small sample size of 63 seasons and scarcity of observed extreme cases warrant additional investigation using model simulations. The following sections present an evaluation of modeled TCs and an analysis of the influence of extreme AMM and ENSO pairs on simulated Atlantic tropical cyclone activity.

5. Atlantic tropical cyclones in the regional climate model

In this section we examine the ability of the regional climate model to represent the observed climatology

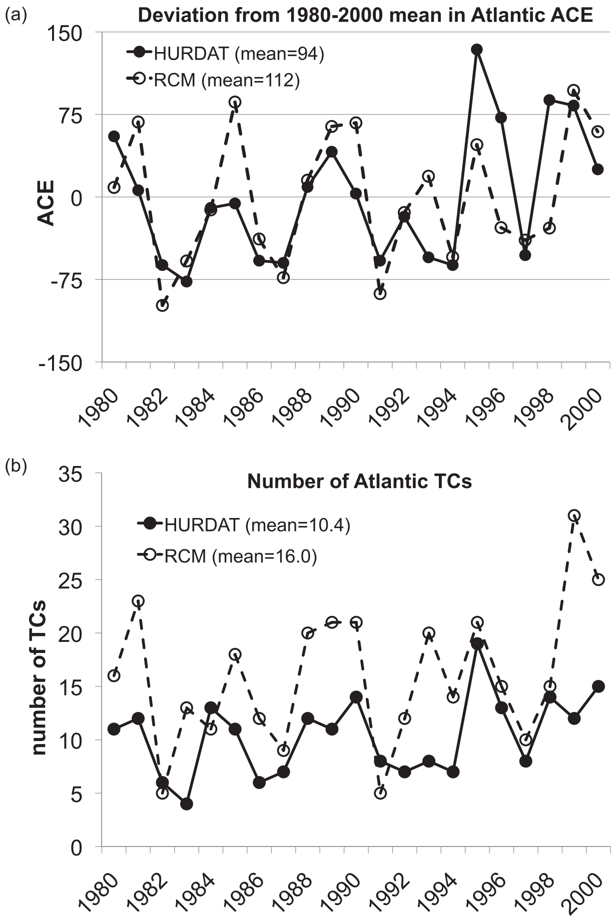

FIG. 4. Time series of (a) deviations from the corresponding 1980–2000 mean (in parentheses) in seasonal ACE ($10^4\,kt^2$) of Atlantic tropical cyclones and (b) seasonal number of Atlantic tropical cyclones, with 1980–2000 mean (in parentheses), from HURDAT2 observations (solid line, closed mark) and the regional climate model control simulation (dashed line, open mark).

TABLE 2. Statistics of Atlantic tropical cyclone seasons over the 1980–2000 period from HURDAT2 observations and the RCM control simulation. Unit of ACE is $10^4\,kt^2$.

	Observations	RCM	Model control simulation bias
ACE mean	94	112	19%
ACE minimum	17	13	−4 ($10^4\,kt^2$)
ACE 25th percentile	36	73	37 ($10^4\,kt^2$)
ACE median	88	100	12 ($10^4\,kt^2$)
ACE 75th percentile	135	171	36 ($10^4\,kt^2$)
ACE maximum	228	209	−19 ($10^4\,kt^2$)
ACE standard deviation	61	59	−2%
No. of tropical cyclones	10.4	16.0	55%

and interannual variability of Atlantic tropical cyclones, as well as observed relationships between Atlantic TCs and modes of Atlantic and Pacific climate variability. This is done to demonstrate the model's suitability to study the impacts of ENSO and AMM on Atlantic TC activity.

Tropical cyclones in the RCM are identified according to the tracking algorithm of Walsh (1997), which includes criteria for a minimum 10-m wind speed of $17.5\,m\,s^{-1}$, a closed minimum in surface pressure, a minimum 850-hPa vorticity threshold over a 5° by 5° region over the TC center, and a warm core. Additional criteria include a duration threshold of at least 2 days and an origin south of 30°N. We refer to tropical cyclones as including tropical storms and hurricanes.

The RCM reproduces the observed interannual variability of 1980–2000 Atlantic ACE (Fig. 4a, correlation $R = 0.58$) and number of Atlantic TCs (Fig. 4b, correlation $R = 0.59$) fairly well. Two simulations using the Geophysical Fluid Dynamics Laboratory (GFDL) regional model at 18-km resolution produce correlations between observed and simulated ACE ($R = 0.72$ and $R = 0.66$, Knutson et al. 2007) comparable to those from the RCM control simulation. In the context of the GFDL simulations, which employ spectral nudging to reanalysis on the domain interior, the performance of the RCM, which does not use nudging in the domain interior, is relatively good.

Tropical cyclone activity is quantified by the seasonal (May–November) total of ACE (Bell et al. 2000, $10^4\,kt^2$), which is preferentially used for the remainder of the study since it is an integrated measure that accounts for storm strength, number, and duration. Although the classical definition of the Atlantic hurricane season is June–November, we perform the analysis for May–November since the model produces a nonnegligible, but still relatively small, number of tropical cyclones in May.

Statistics of Atlantic ACE and number of Atlantic TCs from the control simulation are compared with observations (Table 2). The RCM simulates a 1980–2000 mean seasonal Atlantic ACE of 112, which is 19% greater than the observed mean of 94; in addition, the simulated median of seasonal ACE also exceeds the observed. While the Atlantic ACE during the most active and inactive seasons is fairly similar between the RCM and observations, there is a positive shift in the simulated distribution of ACE relative to observations, with the 25th and 75th percentiles in the control simulation exceeding those of the observations. Despite the bias in the simulated distribution of seasonal Atlantic TC activity, the simulated standard deviation of ACE is nearly identical to the observed, indicating the RCM reproduces variability in seasonal ACE about the mean well.

TABLE 3. Correlations (R) between seasonal Atlantic ACE of HURDAT2 observations and of the RCM control simulation with climate indices over the 1980–2000 period. All climate indices are averaged over August–October. Correlations that are not statistically significant (10% level) are in parentheses. For quantities prescribed in the model (i.e., the Niño-3.4 index, MDR SST, AMO index, and AMM index), the simulated and observed ACE are correlated with the observed quantities. For variables that are calculated by the model (i.e., wind shear) simulated ACE is correlated with the RCM simulated quantities, and observed ACE is correlated with the reanalyzed (NCEP-2) quantities. The MDR includes 9°–21.5°N, 80°–20°W.

	HURDAT2 Atlantic ACE	RCM Atlantic ACE
Niño-3.4 index	−0.63	−0.59
MDR SST	0.59	0.29
AMO index	0.57	(0.21)
AMM index	0.77	0.44
NCEP-2 or RCM MDR vertical wind shear between 850 and 200 hPa	−0.67	−0.71

The RCM simulates too many Atlantic tropical cyclones, 16.0 per season, compared to the observed 10.4 per season (Table 2). This positive bias in number of TCs contributes to the positive ACE bias; however, the ACE bias (19%) is smaller than expected from the bias in number of TCs (55%) because the model produces too few category 3–5 hurricanes (not shown). This weak bias in TC intensity is expected given that the model horizontal resolution is only 27 km—sufficient to represent general TC dynamics but too coarse to fully resolve complete tropical cyclone dynamics. The spatial distribution of TCs in the control simulation compares fairly well with observations; one exception is an underrepresentation of TCs in ''cluster 1'' (Fig. 2c of Daloz et al. (2014, manuscript submitted to *J. Climate*), which represents storms that tend to draw energy from a baroclinic environment (Kossin et al. 2010). In association with the underrepresentation of ''cluster 1'' TCs, there fewer than observed TC landfalls along the east coast of the United States in the control simulation (Fig. 4c of Daloz et al. 2014, manuscript submitted to *J. Climate*).

The RCM reasonably represents observed relationships between Atlantic tropical cyclone activity and Pacific and Atlantic modes of climate variability. The observed correlation between seasonal Atlantic ACE and ASO averaged eastern tropical Pacific SST, represented by the Niño-3.4 index, is $R = -0.63$ during 1980–2000, and the RCM reproduces this well with $R = -0.59$ (Table 3). Observed seasonal Atlantic ACE is positively and significantly correlated with measures of Atlantic SST variability including MDR SST and the AMO and AMM indices (Table 3), with Atlantic ACE most strongly correlated with the AMM index ($R = 0.77$) as in Vimont and Kossin (2007). The RCM simulates positive, but weaker, correlations between Atlantic ACE and these measures of Atlantic SST and, like observations, produces a relationship between Atlantic ACE and the AMM that is stronger than the relationship between ACE and either AMO or MDR SST (Table 3).

Observed relationships between Atlantic tropical cyclone activity and environmental variables important for TCs are also simulated reasonably well in the RCM control simulation (Table 3). Large values of tropospheric vertical wind shear inhibit tropical cyclones (Tuleya and Kurihara 1981; Zehr 1992; DeMaria et al. 1993; Frank and Ritchie 2001; Wong and Chan 2004), and the RCM captures this inverse relationship between ACE and tropospheric vertical wind shear in the MDR, with R of −0.67 in observations and −0.71 in the control simulation.

Based on the evaluation above, we conclude that the RCM is a suitable tool for this study.

6. Influence of ENSO and AMM on Atlantic tropical cyclone activity: RCM simulations

The response in Atlantic ACE to the prescribed ENSO and AMM forcings in the RCM experiments supports the observational analysis, demonstrating that the tropical Pacific and Atlantic climate modes together have a pronounced influence on Atlantic TC activity. This is discussed in detail below, with support from Fig. 5a, which shows seasonal Atlantic ACE from the RCM experiments (Table 1) with the 1980–2000 RCM control mean ($112 \times 10^4\,\mathrm{kt}^2$) for reference, and from Fig. 5b, which shows the ensemble average of seasonal Atlantic ACE from the RCM simulations as a percent of the 1980–2000 mean and in terms of the percentile over the 1950–2012 period of the ASO averaged AMM and Niño-3.4 indices that correspond to the prescribed AMM and ENSO forcings.

The response in environmental conditions relevant for Atlantic TC activity due to the ENSO and AMM forcings prescribed in the RCM simulations is also presented below and diagnosed with the GPI (Emanuel and Nolan 2004) described in section 3c. Figure 6 shows the ensemble and ASO averaged GPI as percent deviation from the 1980–2000 ASO mean from the RCM simulations, together with composites according to ENSO and AMM of the ASO averaged GPI as percent deviation from the 1950–2012 ASO mean computed from the NCEP–NCAR reanalysis (Kalnay et al. 1996), averaged over the MDR and Gulf of Mexico (Fig. 1). The GPI computed from reanalysis is composited using the same

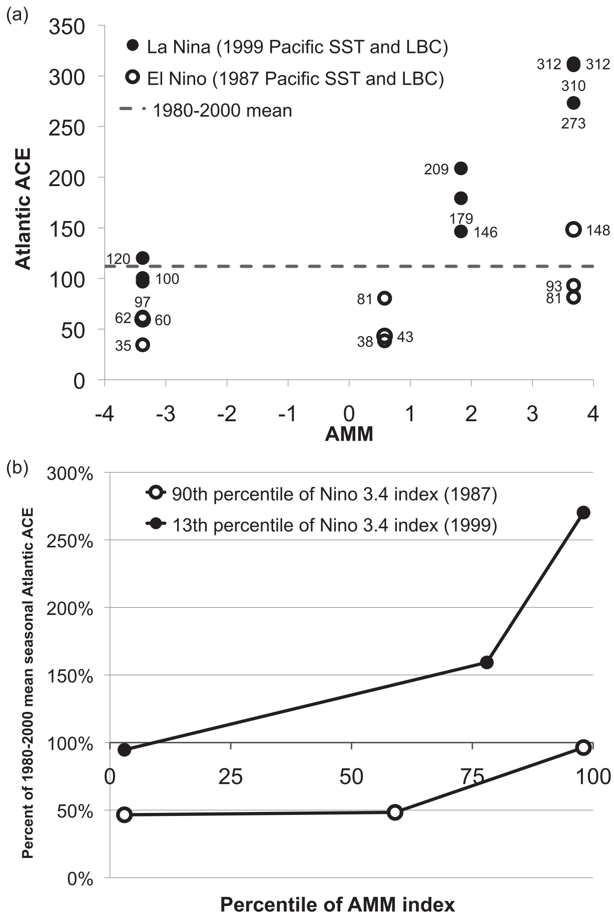

FIG. 5. (a) Seasonal ACE (10^4 kt^2, denoted next to mark) of Atlantic tropical cyclones from RCM simulations forced by the LBCs and Pacific SST of the 1999 La Niña (filled circle) and 1987 El Niño (open circle) and Atlantic SST (corresponding ASO averaged AMM index on the x axis), with the RCM 1980–2000 mean Atlantic ACE (dashes). Each mark represents one season-long integration. (b) As in (a), except ACE is expressed as percent of the 1980–2000 mean, the ASO averaged AMM and Niño-3.4 indices are expressed in terms of percentile over the ASO averaged 1950–2012 period, and each mark corresponds to the RCM experiment ensemble average.

procedure as for the HURDAT2 Atlantic ACE (Fig. 2b). The reanalyzed GPI deviations are generally qualitatively similar in the Gulf of Mexico versus the MDR for ENSO/AMM cases that have a relatively strong deviation in GPI; an exception is the El Niño and neutral AMM case, which is characterized by negative GPI anomalies in the MDR and mixed GPI anomalies in the Gulf of Mexico (not shown). We note caution when comparing the GPI between the RCM simulations and reanalysis, since the RCM simulations represent extreme phases of AMM and ENSO, while the composites from reanalysis include all strengths of AMM and ENSO passing a percentile-based threshold.

To estimate the contribution of each atmospheric factor in supporting the response in GPI, the GPI is also calculated by varying each term while keeping the others fixed at their climatological values (Fig. 6), as in Camargo et al. (2007). Note that since the GPI is nonlinear, the sum of the estimated contribution from individual factors does not equal the GPI. This approach is used to provide an estimate of the primary factors that support simulated changes in the GPI.

a. *TC limiting conditions: El Niño with neutral or negative AMM*

Consistent with the observational analysis, strong El Niño conditions paired with a strongly negative AMM effectively inhibit Atlantic TC activity, with simulated seasonal Atlantic ACE of 35, 60, and 62, compared with the 1980–2000 mean of 112 (Fig. 5a). Under the same El Niño conditions together with a near-neutral AMM, the Atlantic TC activity remains well below average, with seasonal Atlantic ACE of 38, 43, and 81. The ensemble-mean response in Atlantic ACE is nearly equal during the strong (90th percentile) El Niño case paired with Atlantic conditions characterized by an AMM index in both the 0th and 60th percentile (Fig. 5b), supporting the observationally based finding that both unfavorable ENSO and AMM conditions are not required to significantly reduce Atlantic TC activity.

In response to the strong El Niño and near-neutral AMM forcings, the GPI is below average (−13%), with increased vertical wind shear as the largest contributing factor, while the GPI is strongly below average (−55%) due to the strong El Niño and negative AMM forcings, in association with considerable increases in vertical wind shear and decreases in relative humidity and potential intensity (Fig. 6a). It is interesting that although the simulated response in Atlantic ACE is similar due to the concurrent strong El Niño and neutral AMM, and the concurrent strong El Niño and strongly negative AMM forcings (Fig. 5), the reduction in GPI is much larger for the latter than the former. The observational record/reanalysis shows a similar discrepancy between the ACE and GPI, with below average ACE of a similar magnitude for composites according to concurrent El Niño and neutral AMM, as well as El Niño with negative AMM (Fig. 2b), but a negative anomaly in GPI that is much larger for the latter than for the former (Fig. 6b).

This discrepancy between the ACE and GPI may be explained by the threshold response in Atlantic TCs to tropospheric vertical wind shear, with tropical cyclones limited over wind shear of approximately 7.5–10 m s^{-1} (Zehr 1992; DeMaria et al. 1993). While the simulated vertical wind shear between 850 and 200 hPa in the main

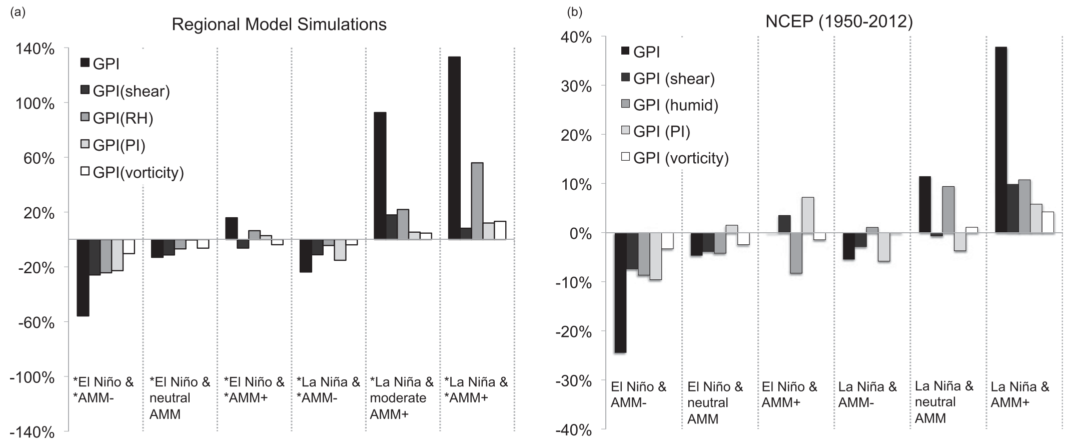

FIG. 6. (a) Percent deviation from the ASO 1980–2000 mean in the ASO averaged GPI index (black) from the ensemble average of the (left to right) 1987_1984Atl, 1987, 1987_2005Atl, 1999_1984Atl, 1999, and 1999_2005Atl RCM simulations. A strong climate mode phase is denoted by an asterisk (*). (b) Composites of percent deviation from the ASO 1950–2012 mean in the ASO averaged GPI index (black) computed from the NCEP–NCAR reanalysis for observed cases of concurrent (left to right) El Niño with negative, neutral, and positive AMM, and La Niña with negative, neutral, and positive AMM. Composites are defined as in Fig. 2b. Also shown are the same values as above, but calculated by varying each term while setting the others fixed at their climatological values, for 850–200-hPa vertical wind shear (dark gray), 600-hPa relative humidity (medium gray), potential intensity (light gray), and 850-hPa vorticity (white). GPI deviations are averaged over the main development region and Gulf of Mexico (hatching in Fig. 1), and positive indicates conditions for tropical cyclones that are more favorable than average.

development region and Gulf of Mexico is stronger than average due to imposed strong El Niño and neutral AMM conditions (Fig. 7a), and much stronger than average in response to strong El Niño and negative AMM (Fig. 7b), the absolute vertical wind shear exceeds $10\,\mathrm{m\,s^{-1}}$ over most of the Atlantic TC development region in response to both sets of conditions (Figs. 7d,e). This suggests that concurrent strong El Niño and neutral AMM are sufficiently limiting for Atlantic tropical cyclone development due to the threshold response in TCs to vertical wind shear; this threshold dependence on vertical wind shear is not included in the GPI, which explains the discrepancy between the ACE and GPI in both the simulations and observations/reanalysis. For comparison, the vertical wind shear is below the $10\,\mathrm{m\,s^{-1}}$ threshold over most of the Atlantic TC development region in response to strong La Niña and moderately positive AMM forcings (Fig. 7f) in association with below average vertical wind shear (Fig. 7c); this permits active tropical cyclone seasons that are also strongly influenced by midtropospheric moisture, as discussed in section 6c.

Reductions in GPI in response to the strong concurrent El Niño and negative AMM forcings are strongest in the western portion of the northern tropical Atlantic, as shown in Fig. 8a, which displays the deviation from the ASO 1980–2000 mean in ASO averaged GPI from the ensemble average of the 1987_1984Atl experiments. In addition, the simulated reduction in GPI is accompanied by a vast reduction in the region of favorable development for Atlantic tropical cyclones, as shown by the contours of Fig. 8a, which denote the ASO averaged GPI value of 0.5 from the 1980–2000 mean and experiment. The value 0.5 is chosen as an example to demonstrate how the spatial pattern of favorable conditions for TCs changes in response to the AMM and ENSO forcings, with regions east of the 0.5 contour relatively unfavorable and west of the 0.5 contour relatively favorable. The relatively favorable environment for TCs is confined to the Gulf of Mexico and northwestern portion of the tropical Atlantic (Fig. 8a), similar to the observed northwest shift in TC genesis during the negative AMM phase relative to the positive phase (Kossin and Vimont 2007).

b. *Destructive interferences: El Niño with positive AMM, La Niña with negative AMM*

In response to strong simultaneous El Niño and positive AMM, the RCM produces a near-average ensemble mean Atlantic ACE of 107 (ACE of 81, 93, and 148 in individual seasons) compared to the simulated control mean of 112 (Fig. 5a). Atlantic TC activity is also near average (ACE of 97, 100, and 120) in response to strong La Niña with strongly negative AMM (Fig. 5a). These RCM experiments support the observational analysis, which indicates that modes of tropical Atlantic and

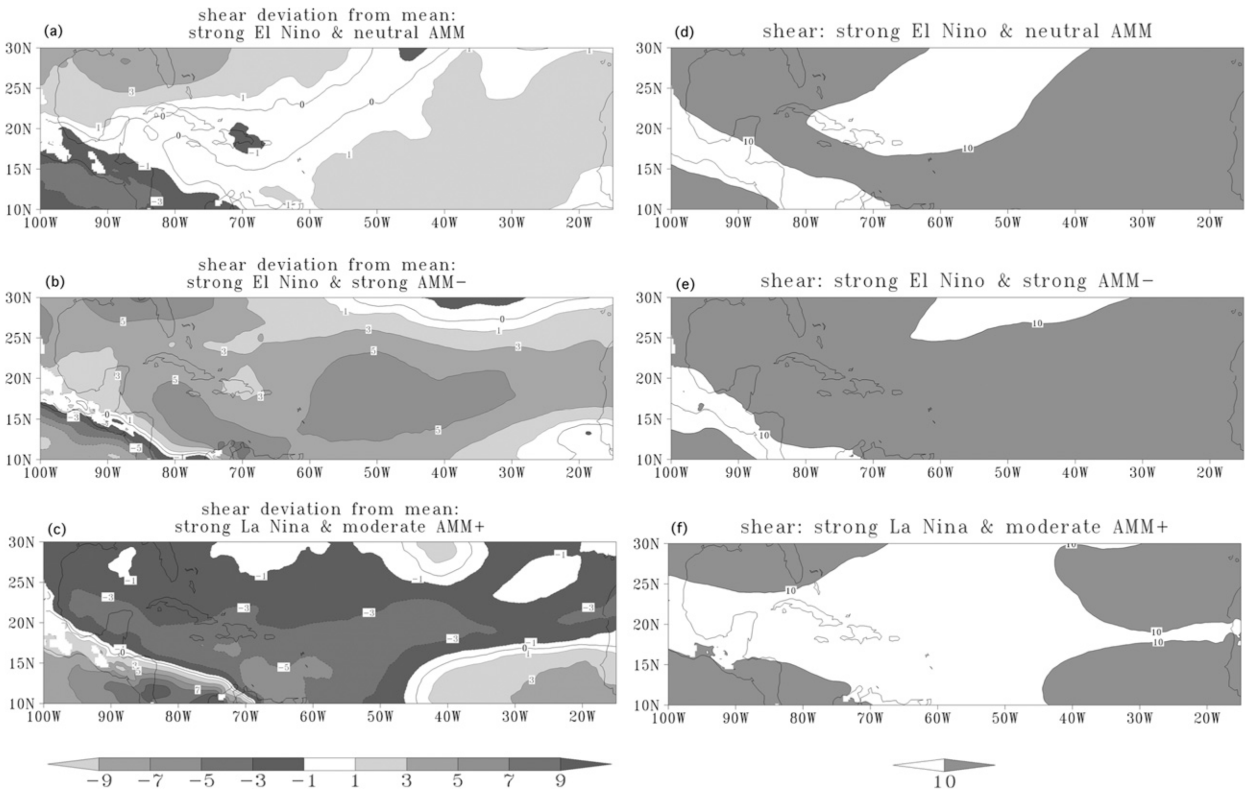

FIG. 7. Deviation from the ASO 1980–2000 mean in the ASO averaged vertical wind shear (m s^{-1}) between 850 and 200 hPa from the ensemble average of the (a) 1987, (b) 1987_1984atl, and (c) 1999 simulations; bold contour is 0 m s^{-1}. Magnitude of the vertical wind shear (m s^{-1}) between 850 and 200 hPa from the ensemble average of the (d) 1987, (e) 1987_1984atl, and (f) 1999 simulations; contour is 10 m s^{-1} and white denotes favorable vertical wind shear for tropical cyclones.

Pacific SST variability individually opposing each other in their influence on Atlantic TCs together produce compensating effects, resulting in insignificant deviations from the mean in Atlantic TC activity.

The idea that the influences on the atmospheric environment of simultaneous La Niña and negative AMM, and simultaneous El Niño and positive AMM, compensate each other is supported by the simulated and reanalyzed GPI. In both the 1999_1984Atl and 1987_2005Atl RCM experiments, the GPI is near average or weakly deviates from the mean (±20%) in association with near-average contributions from each of tropospheric vertical wind shear, 600-hPa relative humidity, potential intensity, and 850-hPa vorticity (Fig. 6a). The reanalysis-based composites produce a similar weak GPI response to La Niña with negative AMM, and to El Niño with positive AMM (Fig. 6b).

While the compensation (in terms of influence on Atlantic TC activity) between competing ENSO and AMM influences is a robust response in both observations and the RCM simulations, it is not clear if there is a dominant influence of AMM, ENSO, or neither. Atlantic ACE in the RCM simulations forced with combinations of strongly opposing ENSO and AMM phases does not show a clear dominating influence of ENSO or AMM (Fig. 5a), with nearly identical ensemble averages in the two RCM experiments (Fig. 5b). In addition, the observed mean ACE during each competing ENSO and AMM pair (i.e., positive AMM with El Niño; negative AMM with Niña) is insignificantly different (10% level) from the mean ACE during the set of all other ENSO and AMM pairs (Fig. 2b).

c. *Constructive interferences: La Niña with positive AMM*

The RCM experiments support the observational analysis in section 4 by producing the most active Atlantic TC seasons in response to both positive AMM and La Niña together. Above average Atlantic tropical cyclone activity is simulated in response to concurrent strong La Niña and moderately positive AMM conditions, and concurrent strong La Niña and *strongly* positive AMM work together constructively to sustain *extremely* active Atlantic TC seasons. Forced by the strong La Niña conditions of 1999, the RCM simulates above average Atlantic ACE of 146, 176, and 209 under a coincident

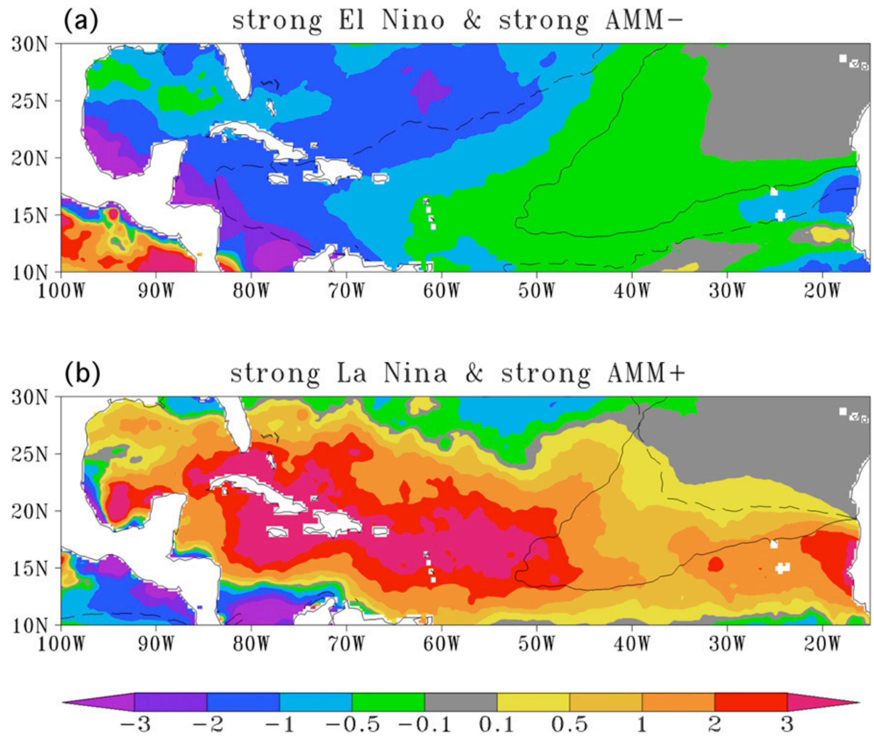

FIG. 8. Deviation from the ASO 1980–2000 mean of the RCM control simulation in the ASO averaged GPI index (unitless; shaded) from the ensemble average of the (a) 1987_1984Atl and (b) 1999_2005Atl RCM experiments, with the ASO average GPI value of 0.5 from the 1980–2000 mean (solid contour) and corresponding RCM experiment (dashed contour). The value 0.5 is chosen as an example to demonstrate how the spatial pattern of favorable environmental conditions for tropical cyclones changes in response to the AMM and ENSO forcings; regions east of the 0.5 contour are relatively unfavorable, and regions west of the 0.5 contour are relatively favorable. Land is white.

moderately positive AMM, and extremely above average Atlantic ACE of 273, 310, 312, and 312 under a coincident strongly positive AMM (Fig. 5a). During strong La Niña conditions there is a nonlinear response in ACE to Atlantic SST conditions described by the AMM, with Atlantic ACE fairly greater for prescribed Atlantic conditions corresponding to an AMM index in the 80th percentile compared to the 0th percentile, but dramatic ACE increases for an AMM index in the 100th percentile (Fig. 5b).

The simulated response in Atlantic ACE to concurrent strong La Niña and strongly positive AMM in each of the four ensemble members exceeds the ACE of the most active observed Atlantic hurricane season, which occurred in 2005 and produced an ACE of 250. Even if we consider the bias in mean Atlantic ACE in the control simulation (Table 2) and scale the ACE of the model experiments accordingly, the ‘‘adjusted’’ ACE values for the concurrent strong La Niña and strongly positive AMM simulations (229, 260, 262, and 262) exceed that observed in the 2005 season in three of four ensemble members. This suggests that the Atlantic may experience hurricane seasons that are more active than the season of 2005 if ‘‘prime’’ conditions in the tropical Atlantic and Pacific occur simultaneously.

The Atlantic ACE of the RCM simulations, which are designed to isolate the influence of ENSO and AMM from other factors, suggests that both strong La Niña and strongly positive AMM are required to support the upper limit of seasonal Atlantic tropical cyclone activity, assuming other factors are equal. This is in rough agreement with the observations, which show that concurrent La Niña and positive AMM support the most above average Atlantic ACE on average (Fig. 2b). We note that, while concurrent La Niña and positive AMM always produced relatively active tropical cyclone seasons, both La Niña and positive AMM were not necessary during some cases of the strongest Atlantic ACE in the observational record (Fig. 2a), including the most active observed season of 2005, which occurred during neutral ENSO conditions; we suspect that, during these cases, variability in factors aside from ENSO and AMM significantly controlled tropical cyclone activity as well.

Comparing the GPI of the RCM simulation forced with a moderately positive AMM and strong La Niña to that derived from reanalysis as the composite including all observed positive AMM and La Niña TC seasons reveals that in both cases, which represent similar but not equal AMM and ENSO conditions, increased midtropospheric relative humidity and decreased tropospheric vertical wind shear support the positive deviations in GPI and ACE (Figs. 6a,b). Similar to the observationally based findings of Vimont and Kossin (2007), multiple atmospheric factors change in ways that cooperate in their influence on Atlantic TCs in response to the AMM forcing in the model simulations (Fig. 6a). In addition, reanalyzed vertical wind shear is positively correlated with the AMM index over the MDR, and negatively correlated with the Niño-3.4 index over the Gulf of Mexico and Caribbean Sea (Fig. 6 of Kossin and Vimont 2007); the reduction in vertical wind shear is located over the MDR, Gulf of Mexico, and Caribbean Sea in response to concurrent moderately positive AMM and strong La Niña forcings in the RCM simulations (Fig. 7c), supporting the idea that positive AMM and La Niña work together constructively in their influence on the atmospheric environment.

We rely on the RCM simulations to understand the influence of strong La Niña and strongly positive AMM on environmental conditions since this extreme case is not represented in the observational record. The GPI indicates that above normal midtropospheric relative humidity is an essential driver for the prime conditions for tropical cyclones during strong La Niña and strongly positive AMM (Fig. 6a). While the strong La Niña and moderately positive AMM produce moderately above average relative humidity and below average vertical wind shear, strongly above normal midtropospheric relative humidity is the main factor supporting the exceedingly favorable conditions for TCs during concurrent strong La Niña and positive AMM (Fig. 6a). The physical mechanism for this response in midtropospheric relative humidity to the AMM SST forcing may be linked to the northward shift of the Atlantic intertropical convergence zone (ITCZ) in association with the positive AMM and to the weakened vertical wind shear in the northern tropical Atlantic associated with La Niña, both conditions that favor deep convection. The enhanced GPI during strong simultaneous La Niña and positive AMM is associated with an eastward expansion of the region favorable for tropical cyclone development relative to the mean (Fig. 8b), similar to Atlantic TC genesis that occurs throughout the tropical Atlantic during the AMM positive phase and is located farther east in comparison with the AMM negative phase (Kossin and Vimont 2007).

We note that the results presented in this section are based on atmosphere-only model simulations forced with prescribed SST, and thus do not take into full account atmosphere–ocean feedbacks in the development of the AMM and ENSO. Future studies are needed to examine how air–sea feedbacks, such as the WES, can affect the influence of the AMM on TCs.

7. Conclusions

The influence of eastern tropical Pacific SST variability during the El Niño–Southern Oscillation on seasonal Atlantic tropical cyclone activity is well documented, with warmer than average SST during El Niño inhibiting Atlantic TCs (e.g., Gray 1984; Goldenberg and Shapiro 1996; Tang and Neelin 2004). Atlantic SST variability also significantly influences Atlantic tropical cyclone activity; the relationship between Atlantic TC activity and the meridional gradient between northern and southern tropical Atlantic SST, which is characterized by the Atlantic meridional mode, is strong on both interannual and decadal time scales (Vimont and Kossin 2007). In this study, we quantify the impact of concurrent extreme phases of ENSO and AMM on seasonal Atlantic TC activity and the atmospheric environment using observations and regional climate model experiments.

Composites of observed Atlantic accumulated cyclone energy (ACE) reveal that individually ENSO or AMM alone provides an incomplete explanation of seasonal Atlantic tropical cyclone variability and that both are primary influences on Atlantic TC activity (i.e., the AMM does not act as a secondary influence to modulate the impact of ENSO). On average, the upper limit of seasonal Atlantic tropical cyclone activity requires a positive AMM and La Niña together, while significantly reduced seasonal Atlantic TC activity does not require both unfavorable ENSO and AMM conditions. In addition, a warm ENSO phase is generally not a sufficient condition for below average Atlantic TC activity since a positive AMM phase exerts a compensating influence.

Regional climate model simulations are used to augment the observational analysis, which is based on a relatively small sample size of 63 seasons, and potentially lacks rare occurrences of concurrent extreme ENSO and AMM phases. Simulations at 27-km resolution are performed with WRF. The control simulation uses observed SST and lateral boundary conditions of 1980–2000, and experiments are forced with ENSO phases through LBCs and eastern tropical Pacific SST and AMM phases through Atlantic SST. Each prescribed ENSO and AMM phase is based on an observed case.

The RCM simulations produce relationships between Atlantic tropical cyclone activity and concurrent AMM and ENSO phases that are consistent with the observational analysis and improve our understanding of the influence of extreme phases of Atlantic and Pacific climate modes on Atlantic TCs:

- Strong concurrent La Niña and positive AMM work together constructively to sustain extremely active Atlantic TC seasons primarily through above average midtropospheric relative humidity with below average tropospheric vertical wind shear, which produce an extensive region of conditions favorable for TCs. Under strong La Niña conditions, Atlantic TC activity responds nonlinearly to AMM, with dramatic increases for extremely warm Atlantic SST conditions. This combination of "prime" Atlantic and Pacific conditions supports simulated Atlantic hurricane seasons that are more active than the most active season currently on record, 2005.
- Strong phases of ENSO and AMM that individually oppose each other in their influence on Atlantic TCs together produce compensating effects and support near-average Atlantic tropical cyclone activity and environmental conditions relevant for TCs in the Atlantic development region.
- Strong concurrent El Niño and negative AMM are not required to effectively inhibit Atlantic TC activity because the threshold in tropospheric vertical wind shear that suppresses TCs can be achieved without this combination of the most unfavorable Pacific and Atlantic conditions.

This work emphasizes that understanding Atlantic tropical cyclone activity relies critically on considering both ENSO and AMM, with the implication that future predictions of Atlantic TC activity require knowledge of the distribution of seasonal tropical Atlantic and Pacific SST, not just climatological mean SST changes. Although this study does not address seasonal TC prediction directly, it may be applied to guide predictions of Atlantic TC activity, especially for seasons occurring during extreme AMM and ENSO phases, remembering that other factors including upper tropospheric temperature variability, African easterly wave activity, and Saharan dust also play an important role and are not to be neglected.

Acknowledgments. This research is supported by U.S. National Science Foundation Grants AGS-1067937 and AGS-1347808, Department of Energy Grants DE-SC0004966 and DE-SC0006824, and National Oceanic and Atmospheric Administration Grant NA11OAR4310154. PC acknowledges the support from the National Science Foundation of China (41028005, 40921004, and 40930844) and the Chinese Ministry of Education's 111 project (B07036). CP acknowledges support from the University Corporation for Atmospheric Research (UCAR) Joint Office for Science Support (JOSS). The Texas Advanced Computing Center (TACC) at The University of Texas at Austin and the Texas A&M Supercomputing Facility provided high-performance computing resources that contributed to the research results reported in this paper. CP wishes to thank Jen-Shan Hsieh for sharing his TC tracking routine. The Fortran subroutine to calculate potential intensity was written by Kerry Emanuel and is available at http://eaps4.mit.edu/faculty/Emanuel/products. HURDAT2 available from the Atlantic Oceanographic and Meteorological Laboratory/National Oceanic and Atmospheric Administration (AOML/NOAA) Hurricane Research Division (HRD) website at http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html. The AMM index is calculated by Daniel J. Vimont at the University of Wisconsin–Madison and provided by the NOAA Earth System Research Laboratory (ESRL). The Niño-3.4 index is provided by the NOAA Climate Prediction Center (CPC). AMM and Niño-3.4 data are obtained from http://www.esrl.noaa.gov/psd/data/climateindices/list/. NCEP-2 and NCEP CFSR data are obtained from the NOAA National Operational Model Archive & Distribution System (NOMADS). We thank the members of the CLIVAR Hurricane WG for helpful discussions and are grateful to Philip J. Klotzbach and two anonymous reviewers for their insightful comments, which improved this paper significantly.

REFERENCES

Arkin, P. A., 1982: The relationship between interannual variability in the 200-mb tropical wind field and the Southern Oscillation. *Mon. Wea. Rev.,* **110,** 1393–1404, doi:10.1175/1520-0493(1982)110<1393:TRBIVI>2.0.CO;2.

Avila, L. A., 1991: Atlantic tropical systems of 1990. *Mon. Wea. Rev.,* **119,** 2027–2033, doi:10.1175/1520-0493(1991)119<2027:ATSO>2.0.CO;2.

Belanger, J. I., V. T. Toma, J. A. Curry, P. J. Webster, and M. T. Jelinek, 2014: Climate dynamics of easterly waves in the North Atlantic and east Pacific. *31st Conf. on Hurricanes and Tropical Meteorology,* San Diego, CA, Amer. Meteor. Soc., 1A.6. [Available online at https://ams.confex.com/ams/31Hurr/webprogram/Paper245355.html.]

Bell, G. D., and M. Chelliah, 2006: Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *J. Climate,* **19,** 590–612, doi:10.1175/JCLI3659.1.

——, and Coauthors, 2000: Climate assessment for 1999. *Bull. Amer. Meteor. Soc.,* **81,** s1–s50, doi:10.1175/1520-0477(2000)81[s1:CAF]2.0.CO;2.

——, M. Chelliah, K. Mo, S. B. Goldenberg, C. W. Landsea, E. Blake, and R. Pasch, 2005: NOAA: August 2005 update to Atlantic hurricane season outlook. [Available online at http://www.cpc.ncep.noaa.gov/products/outlooks/hurricane2005/August/hurricane.html.]

Bister, M., and K. A. Emanuel, 1998: Dissipative heating and hurricane intensity. *Meteor. Atmos. Phys.,* **65,** 233–240, doi:10.1007/BF01030791.

——, and ——, 2002: Low frequency variability of tropical cyclone potential intensity. 1. Interannual to interdecadal variability. *J. Geophys. Res.,* **107,** 4801, doi:10.1029/2001JD000776.

Bove, M. C., J. J. O'Brien, J. B. Eisner, C. W. Landsea, and X. Niu, 1998: Effect of El Niño on U.S. landfalling hurricanes, revisited. *Bull. Amer. Meteor. Soc.,* **79,** 2477–2482, doi:10.1175/1520-0477(1998)079<2477:EOENOO>2.0.CO;2.

Camargo, S. J., K. A. Emanuel, and A. H. Sobel, 2007: Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis. *J. Climate,* **20,** 4819–4834, doi:10.1175/JCLI4282.1.

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air–sea interactions. *Nature,* **385,** 516–518, doi:10.1038/385516a0.

——, Y. Fang, R. Saravanan, L. Ji, and H. Seidel, 2006: The cause of the fragile relationship between the Pacific El Niño and the Atlantic Niño. *Nature,* **443,** 324–328, doi:10.1038/nature05053.

Chiang, J. C. H., and D. J. Vimont, 2004: Analogous Pacific and Atlantic meridional modes of tropical atmosphere–ocean variability. *J. Climate,* **17,** 4143–4158, doi:10.1175/JCLI4953.1.

Curtis, S., and S. Hastenrath, 1995: Forcing of anomalous sea surface temperature evolution in the tropical Atlantic during Pacific warm events. *J. Geophys. Res.,* **100,** 15 835–15 847, doi:10.1029/95JC01502.

Czaja, A., P. van der Vaart, and J. Marshall, 2002: A diagnostic study of the role of remote forcing in tropical Atlantic variability. *J. Climate,* **15,** 3280–3290, doi:10.1175/1520-0442(2002)015<3280:ADSOTR>2.0.CO;2.

DeMaria, M., J.-J. Baik, and J. Kaplan, 1993: Upper-level eddy angular momentum flux and tropical cyclone intensity change. *J. Atmos. Sci.,* **50,** 1133–1147, doi:10.1175/1520-0469(1993)050<1133:ULEAMF>2.0.CO;2.

Dunstone, N. J., D. M. Smith, B. B. B. Booth, L. Hermanson, and R. Eade, 2013: Anthropogenic aerosol forcing of Atlantic tropical storms. *Nat. Geosci.,* **6,** 534–539, doi:10.1038/ngeo1854.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.,* **52,** 3969–3976, doi:10.1175/1520-0469(1995)052<3969:SOTCTS>2.0.CO;2.

——, 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature,* **436,** 686–688, doi:10.1038/nature03906.

——, and D. Nolan, 2004: Tropical cyclone activity and global climate. Preprints, *26th Conf. on Hurricanes and Tropical Meteorology,* Miami, FL, Amer. Meteor. Soc., 240–241.

Enfield, D. B., and D. A. Mayer, 1997: Tropical Atlantic sea surface temperature variability and its relation to El Niño–Southern Oscillation. *J. Geophys. Res.,* **102,** 929–945, doi:10.1029/96JC03296.

Evan, A. T., J. Dunion, J. A. Foley, A. K. Heidinger, and C. S. Velden, 2006: New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks. *Geophys. Res. Lett.,* **33,** L19813, doi:10.1029/2006GL026408.

Frank, W. M., and E. A. Ritchie, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev.,* **129,** 2249–2269, doi:10.1175/1520-0493(2001)129<2249:EOVWSO>2.0.CO;2.

Giannini, A., Y. Kushnir, and M. A. Cane, 2000: Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *J. Climate,* **13,** 297–311, doi:10.1175/1520-0442(2000)013<0297:IVOCRE>2.0.CO;2.

Goldenberg, S. B., and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Climate,* **9,** 1169–1187, doi:10.1175/1520-0442(1996)009<1169:PMFTAO>2.0.CO;2.

——, C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science,* **293,** 474–479, doi:10.1126/science.1060040.

Gray, W. M., 1979: Hurricanes: Their formation, structure and likely role in the tropical circulation. *Meteorology over the Tropical Oceans,* D. B. Shaw, Ed., Royal Meteorological Society, 155–218.

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

——, and P. J. Klotzbach, 2005: Extended range forecast of Atlantic seasonal hurricane activity, individual monthly activity, and U.S. landfall strike probability for 2005. [Available online at http://hurricane.atmos.colostate.edu/forecasts/2005/aug2005/.]

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S. K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP-DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.,* **83,** 1631–1643, doi:10.1175/BAMS-83-11-1631.

Klein, S. A., B. J. Soden, and N.-C. Lau, 1999: Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *J. Climate,* **12,** 917–932, doi:10.1175/1520-0442(1999)012<0917:RSSTVD>2.0.CO;2.

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

——, and W. M. Gray, 2008: Multidecadal variability in North Atlantic tropical cyclone activity. *J. Climate,* **21,** 3929–3935, doi:10.1175/2008JCLI2162.1.

——, and ——, 2013: Summary of the 2013 Atlantic tropical cyclone activity and verification of authors' seasonal and two-week forecasts. 66 pp. [Available online at http://tropical.atmos.colostate.edu/forecasts/2013/nov2013/nov2013.pdf.]

Knutson, T. R., J. J. Sirutis, S. T. Garner, I. M. Held, and R. E. Tuleya, 2007: Simulation of the recent multidecadal increase of Atlantic hurricane activity using an 18-km-grid regional model. *Bull. Amer. Meteor. Soc.,* **88,** 1549–1565, doi:10.1175/BAMS-88-10-1549.

Kossin, J. P., and D. J. Vimont, 2007: A more general framework for understanding Atlantic hurricane variability and trends. *Bull. Amer. Meteor. Soc.,* **88,** 1767–1781, doi:10.1175/BAMS-88-11-1767.

——, S. J. Camargo, and M. Sitkowski, 2010: Climate modulation of North Atlantic hurricane tracks. *J. Climate,* **23,** 3057–3076, doi:10.1175/2010JCLI3497.1.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.,* **121,** 1703–1713, doi:10.1175/1520-0493(1993)121<1703:ACOIMA>2.0.CO;2.

——, and J. L. Franklin, 2013: Atlantic hurricane database uncertainty and presentation of a new database format. *Mon. Wea. Rev.,* **141,** 3576–3592, doi:10.1175/MWR-D-12-00254.1.

——, R. A. Pielke Jr., A. M. Mestas-Nuñez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climate changes. *Climatic Change,* **42,** 89–129, doi:10.1023/A:1005416332322.

——, and Coauthors, 2004: The Atlantic hurricane database reanalysis project: Documentation for the 1851–1910 alterations and additions to the HURDAT database. *Hurricanes and Typhoons: Past, Present, and Future,* R. J. Murnane and K.-B. Liu, Eds., Columbia University Press, 177–221.

Mann, M. E., and K. A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *Eos, Trans. Amer. Geophys. Union,* **87,** 233–241, doi:10.1029/2006EO240001.

Mo, K. C., and S. Häkkinen, 2001: Interannual variability in the tropical Atlantic and linkages to the Pacific. *J. Climate,* **14,** 2740–2762, doi:10.1175/1520-0442(2001)014<2740:IVITTA>2.0.CO;2.

Nobre, P., and J. Shukla, 1996: Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate,* **9,** 2464–2479, doi:10.1175/1520-0442(1996)009<2464:VOSSTW>2.0.CO;2.

Pielke, R. A., Jr., and C. W. Landsea, 1999: La Niña, El Niño, and Atlantic hurricane damages in the United States. *Bull. Amer. Meteor. Soc.,* **80,** 2027–2033, doi:10.1175/1520-0477(1999)080<2027:LNAENO>2.0.CO;2.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.,* **108,** 4407, doi:10.1029/2002JD002670.

Saravanan, R., and P. Chang, 2000: Interaction between tropical Atlantic variability and El Niño–Southern Oscillation. *J. Climate,* **13,** 2177–2194, doi:10.1175/1520-0442(2000)013<2177:IBTAVA>2.0.CO;2.

Servain, J., I. Wainer, J. P. McCreary, and A. Dessier, 1999: Relationship between the equatorial and meridional modes of climatic variability in the tropical Atlantic. *Geophys. Res. Lett.,* **26,** 485–488, doi:10.1029/1999GL900014.

Skamarock, W. C., and Coauthors, 2008: A description of the Advanced Research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp. [Available online at http://www.mmm.ucar.edu/wrf/users/docs/arw_v3_bw.pdf.]

Smirnov, D., and D. J. Vimont, 2011: Variability of the Atlantic meridional mode during the Atlantic hurricane season. *J. Climate,* **24,** 1409–1424, doi:10.1175/2010JCLI3549.1.

Smith, S. R., J. Brolley, J. J. O'Brien, and C. A. Tartaglione, 2007: ENSO's impact on regional U.S. hurricane activity. *J. Climate,* **20,** 1404–1414, doi:10.1175/JCLI4063.1.

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. Climate,* **21,** 2283–2296, doi:10.1175/2007JCLI2100.1.

Tang, B. H., and J. D. Neelin, 2004: ENSO influence on Atlantic hurricanes via tropospheric warming. *Geophys. Res. Lett.,* **31,** L24204, doi:10.1029/2004GL021072.

Tuleya, R. E., and Y. Kurihara, 1981: A numerical study on the effects of environmental flow on tropical storm genesis. *Mon. Wea. Rev.,* **109,** 2487–2506, doi:10.1175/1520-0493(1981)109<2487:ANSOTE>2.0.CO;2.

U.S. CLIVAR, 2011: U.S. CLIVAR launches two new working groups. *U.S. CLIVAR Variations,* **9** (1), U.S. CLIVAR Project Office, Washington, DC, 12 pp. [Available online at http://www.usclivar.org/sites/default/files/Variations-V9N1-1.pdf.]

Vimont, D. J., and J. P. Kossin, 2007: The Atlantic meridional mode and hurricane activity. *Geophys. Res. Lett.,* **34,** L07709, doi:10.1029/2007GL029683.

Vitart, F., and J. L. Anderson, 2001: Sensitivity of Atlantic tropical storm frequency to ENSO and interdecadal variability of SSTs in an ensemble of AGCM integrations. *J. Climate,* **14,** 533–545, doi:10.1175/1520-0442(2001)014<0533:SOATSF>2.0.CO;2.

Walsh, K., 1997: Objective detection of tropical cyclones in high-resolution analyses. *Mon. Wea. Rev.,* **125,** 1767–1779, doi:10.1175/1520-0493(1997)125<1767:ODOTCI>2.0.CO;2.

Wang, X., C. Wang, W. Zhou, D. Wang, and J. Song, 2011: Teleconnected influence of North Atlantic sea surface temperature on the El Niño onset. *Climate Dyn.,* **37,** 663–676, doi:10.1007/s00382-010-0833-z.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science,* **309,** 1844–1846, doi:10.1126/science.1116448.

Wong, M. L. M., and J. C. L. Chan, 2004: Tropical cyclone intensity in vertical wind shear. *J. Atmos. Sci.,* **61,** 1859–1876, doi:10.1175/1520-0469(2004)061<1859:TCIIVW>2.0.CO;2.

Xie, S.-P., and Y. Tanimoto, 1998: A pan-Atlantic decadal climate oscillation. *Geophys. Res. Lett.,* **25,** 2185–2188, doi:10.1029/98GL01525.

Zehr, R. M., 1992: Tropical cyclogenesis in the western North Pacific. NOAA Tech. Rep. NESDIS 61, 181 pp.

Zhu, X., R. Saravanan, and P. Chang, 2012: Influence of mean flow on the ENSO–vertical wind shear relationship over the northern tropical Atlantic. *J. Climate,* **25,** 858–864, doi:10.1175/JCLI-D-11-00213.1.