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Key Points:

- Wintertime MDR SST anomalies can persist into subsequent summer, explaining 42% of interannual variance of SST in the hurricane season
- Except wind-evaporation-SST and cloud-SST feedbacks, water vapor feedback process also plays an important role in the persistence of winter MDR SST
- The water vapor feedback influences the seasonal evolution of MDR SST by modulating seasonal variations of downward longwave radiation

Supporting Information:

- Supporting Information S1

Correspondence to:
H. Liu,
liuhailong@gmail.com

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Persistent influence of tropical North Atlantic wintertime sea surface temperature on the subsequent Atlantic hurricane season

Xidong Wang[1], Hailong Liu[2], and Gregory R. Foltz[3]

[1]College of Oceanography, Hohai University, Nanjing, China, [2]Institute of Oceanography, Shanghai Jiaotong University, Shanghai, China, [3]NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida, USA

Abstract This study explores the seasonally lagged impact of wintertime sea surface temperature (SST) in the Atlantic main development region (MDR) on the subsequent Atlantic hurricane season. It is found that wintertime SST anomalies in the MDR can persist into the summer, explaining 42% of the variance in the subsequent hurricane season's SST during 1951–2010. An anomalously warm wintertime in the MDR is usually followed by an anomalously active hurricane season. Analysis shows an important constraint on the seasonal evolution of the MDR SST by the water vapor feedback process, in addition to the well-known wind-evaporation-SST and cloud-SST feedback mechanisms over the tropical North Atlantic. The water vapor feedback influences the seasonal evolution of MDR SST by modulating seasonal variations of downward longwave radiation. This wintertime thermal control of hurricane activity has significant implications for seasonal predictions and long-term projections of hurricane activity over the North Atlantic.

1. Introduction

Tropical cyclones over the North Atlantic are capable of producing enormous social, economic, and environmental effects on the countries adjacent to the North Atlantic and even long-lasting effects on the global climate. For example, Hurricane Katrina formed in the record-breaking Atlantic hurricane season of 2005 and is the costliest natural disaster in the history of the United States, with total property loss of $108 billion and 1245 deaths due to the strong winds and subsequent floods [*Knabb et al.*, 2005]. Observational and modeling evidence also show that the vigorous mixing of tropical cyclones can pump large amounts of heat into the ocean interior, impacting oceanic heat transport, heat uptake, and the oceanic meridional overturning circulation [*Emanuel*, 2001; *Sriver and Huber*, 2007; *Pasquero and Emanuel*, 2008; *Korty et al.*, 2008; *Jansen and Ferrari*, 2009; *Jansen et al.*, 2010; *Hu and Meehl*, 2009; *Fedorov et al.*, 2010; *Mei et al.*, 2013; *Wang et al.*, 2014].

From a thermodynamic point of view, it is widely accepted that the formation and development of tropical cyclones are closely associated with the underlying sea surface temperature (SST) [*Emanuel*, 1999]. Several studies have shown that tropical SST variability accounts for most of the variance of the frequency and intensity of global tropical cyclones [e.g., *Emanuel*, 2005; *Webster et al.*, 2005; *Hoyos et al.*, 2006; *Klotzbach*, 2006]. Over the North Atlantic, the role of SST in synoptic, interannual, and decadal tropical cyclone activity has been extensively examined and discussed [e.g., *Landsea et al.*, 1999; *Goldenberg et al.*, 2001; *Mann and Emanuel*, 2006; *Zhang and Delworth*, 2006; *Trenberth and Shea*, 2006; *Klotzbach et al.*, 2015]. *Foltz and McPhaden* [2006] revealed that the record-breaking Atlantic hurricane season of 2005 occurred during a period of the anomalously warm SST and a weakening of the northeasterly trade winds throughout most of the Tropical North Atlantic (TNA). It has also been suggested that the increased Atlantic hurricane activity since 1995 is partly attributable either to TNA SST fluctuations associated with the Atlantic multidecadal oscillation (AMO) or the TNA SST warming trend linked to the global warming [e.g., *Goldenberg et al.*, 2001; *Mann and Emanuel*, 2006]. A statistical model study showed that SST warming of 0.5°C in the TNA tends to cause a 40% increase in hurricane frequency and activity [*Saunders and Lea*, 2008].

Previous studies mainly identified the effects of hurricane season SST variability on interannual and long-term hurricane activity over the North Atlantic. However, due to the mismatch in timing, the role of the preceding seasons' SST variability for hurricane activity in the subsequent hurricane season has mostly been neglected. In fact, it may be substantially important for seasonal hurricane prediction. *Elsner et al.* [2006] showed that their statistical model has considerable skill in predicting U.S. land-falling hurricanes several months in advance. They attributed the skill in part to persistence of winter-spring TNA SST anomalies into the summer. However, they stated only that there is a statistically significant relationship between the AMO and basin-wide hurricane counts. Klotzbach and Bell ("Extended range forecast of Atlantic seasonal hurricane activity and landfall strike probability for 2017," available from webcms.colostate.edu/tropical/media/sites/111/2017/04/2017-4.pdf) noted a positive correlation (0.56) between January–March SST averaged between 5°S–35°N and 10°W–40°W and Atlantic accumulated cyclone energy (ACE) during 1982–2010. However, details of the winter–spring SST persistence and its mechanisms remain unclear.

Here we show the importance of the preceding wintertime SST anomalies on hurricane activity over the North Atlantic through analysis of atmospheric and oceanic observations and reanalysis data. The rest of this paper is organized as follows. Section 2 introduces the data sets and methods used in this paper. Sections 3 and 4 investigate the effect of the preceding wintertime SST anomalies on the hurricane activity and analyze the corresponding mechanisms. A brief conclusion and discussion are given in section 5.

2. Data and Methods

The 6 h tropical cyclone best track data set during 1951–2010 is obtained from National Hurricane Centers HURricane DATabase 2 (HURDAT2), archived by the International Best Track Archive for Climate Stewardship in the North Atlantic [*Knapp et al*., 2010]. Tropical cyclones are classified into tropical depressions, tropical storms, and hurricanes according to the Saffir-Simpson hurricane scale, and major hurricanes include Categories 3–5. June–November (JJASON) is referred to as the hurricane season in this paper since most of the tropical cyclones in Atlantic basin occur between June and November [e.g., *Wang et al*., 2017]. The main development region (MDR) of Atlantic hurricanes is defined as the region within 10°N–20°N, 85°W–15°W, which is similar to that used by *Goldenberg and Shapiro* [1996]. The hurricane frequency and activity considered here include the number of tropical storms (≥62.968 km/h including subtropical storms), number of hurricanes (≥64 knots), number of major hurricanes (≥177.792 km/h), and ACE. ACE is a measure of seasonally integrated hurricane activity that depends on the number of storms, their duration, and their intensity over their lifetime [*Bell and Chelliah*, 2006]. As the uncertainty is substantial in the presatellite era regarding tropical cyclone activity [*Landsea and Franklin*, 2013], we compare the results of this study versus those of using the data during 1970–2010 and they are consistent (not shown). Therefore, we use the data set from 1951 throughout this study.

The monthly data set of the extended reconstructed SST version 3 is used and obtained from the NOAA National Climatic Data Center, with a horizontal resolution of 2° × 2° [*Smith et al*., 2008]. The atmospheric data set is the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis [*Kalnay et al*., 1996]. The atmospheric variables used in this study include 10 m wind, 925 hPa wind vectors, vertical wind shear between 200 hPa and 850 hPa, surface latent heat flux, net shortwave radiation, net longwave radiation, sensible heat flux, cloud forcing net longwave flux, downward longwave radiation flux, total cloud cover, and precipitable water content.

The statistical methods of linear correlation and statistical composites are used in this study. For the significance test of correlation, we calculate the effective degrees of freedom [e.g., *Quenouille*, 1952; *Medhaug and Furevik*, 2011; *Wang et al*., 2012] as $N_E = N/(1 + 2R_{X1}R_{Y1} + 2R_{X2}R_{Y2})$, where N is the numbers of data points for the time series of X and Y; R_{X1} or R_{Y1} is the autocorrelation at lag 1; and R_{X2} or R_{Y2} is the autocorrelation at lag 2.

Previous studies showed that the SST variability over the tropical Atlantic poleward of 10°N is dominated by the annual cycle of heat flux, implying that the warming (cooling) of the sea surface is highly correlated with the increased (decreased) heat flux [*Foltz et al*., 2003; *Yu et al*., 2006]. Therefore, in this study we mainly focus on the effect of surface heat flux feedback on the persistence of the winter MDR SST anomalies and do not consider ocean dynamics, which include horizontal heat advection and vertical entrainment.

3. Persistent Effect of the Winter MDR SST Anomalies on Hurricane Activity

Figure 1a shows the correlations between wintertime SST (Jan–Mar, JFM) in the Atlantic MDR and each following month's SST. The correlation decreases gradually with increasing lag time and reaches a minimum in October. Beginning in early winter, the seasonal autocorrelation starts increasing slightly again, possibly

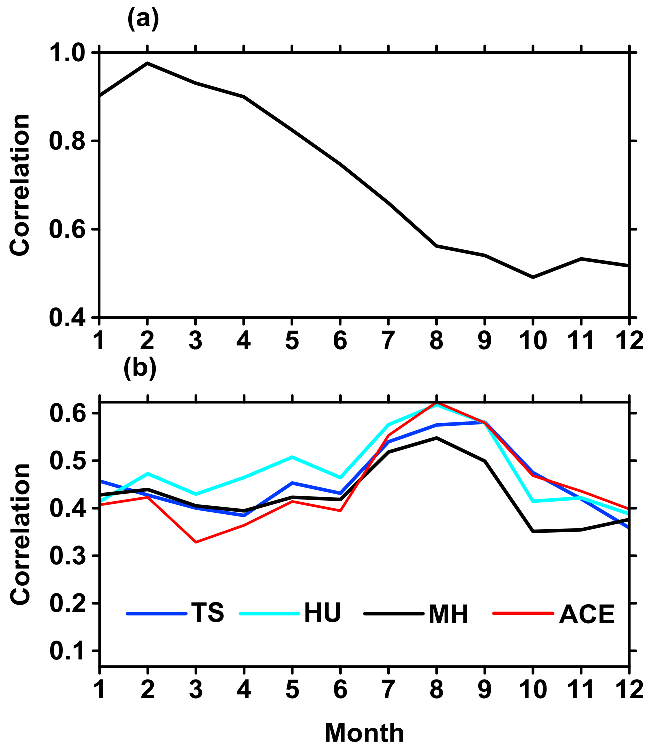

Figure 1. (a) Correlations between JFM MDR SST and each month's MDR SST during 1951–2010. (b) Correlations between June–November hurricane activity and each month's MDR SST during 1951–2010. For short, tropical storm, hurricane, and major hurricane are called TS, HU, and MH.

due to the SST anomalies' resurgence associated with mixed-layer deepening in late fall [*Alexander and Deser*, 1995]. The lag correlation coefficients are greater than 0.5 throughout the hurricane season and are statistically significant at the 99.9% confidence level. The correlation coefficient between wintertime and hurricane season (June–November) SST is 0.65, meaning that 42% of variance of subsequent hurricane season SST during 1951–2010 is linked to the winter SST anomalies. Figure 1b shows correlation coefficients between monthly MDR SST and JJASON hurricane activity. The correlation between JFM MDR SST and the number of tropical cyclones in the hurricane season is 0.45, which is significant at the 99.9% confidence level. The monthly correlation coefficients are relatively high throughout the hurricane season, with an average correlation coefficient of 0.54. However, after the effect of wintertime SST is removed, the partial correlation between JJASON SST and the number of tropical storms reduces to 0.37. Results are similar for other hurricane measures such as the number of hurricanes, major hurricanes, and ACE. These results indicate the important effect of the preceding wintertime SST anomalies on hurricane activity.

To highlight the link between wintertime SST variations and hurricane activity over the North Atlantic, we compare the records of hurricanes for the preceding winter warm and cold SST anomaly years. Here we define the winter warm and cold years based on when the winter regionally averaged MDR SST anomaly is greater than one standard deviation and less than negative one standard deviation, respectively, using data from 1951 to 2010. Using the above criteria, we identify 10 warm and 10 cold years (Table 1). Most of the winter cold years occur before 1996, as a result of the negative AMO phase. In contrast, since the mid-1990s, the occurrence of winter warm years has been increasing at the expense of winter cold years (Table 1). The 10-winter warm composite pattern of SST anomalies shows the well-known tripole-like SST pattern over the North Atlantic consisting of cold SST anomalies in the subtropics and warm anomalies over the TNA. Also, warm anomalies are located to the north of 40°N (Figure 2a). In contrast, the composite SST anomalies for the 10 cold years shows a nearly opposite pattern (Figure 2b).

A clear difference between tropical cyclone formation during winter warm and cold years can be seen in Figure 2. During the subsequent hurricane season associated with winter warm years, 43 major hurricanes occur in the North Atlantic, compared to 15 major hurricanes during the subsequent hurricane season associated with winter cold years, a ratio of 2.9 to 1. The number of tropical storms, number of hurricanes, and ACE

Table 1. Winter Warm and Cold Years[a]

Type of Winter Year	Years
Winter Warm Years	1958, 1969, 1970, 1996, 1998, 2002, 2004, 2005, 2007, 2010
Winter cold years	1957, 1965, 1972, 1974, 1975, 1976, 1985, 1986,1989,1994

[a]They are defined as the years when the MDR regionally averaged winter (January–March) SST anomaly is greater than one standard deviation and less than negative one standard deviation, respectively.

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also show that the overall activity is higher in the corresponding winter warm years than in the winter cold years (Figures S1 and S2 in the supporting information).

The monthly averaged tropical cyclone number and ACE from June to November for the wintertime warm and cold year composites, along with the monthly average climatology of tropical cyclone number and ACE, are shown in Figure S2. Climatologically, the largest number of tropical cyclones occurs during August to October. The significant differences in the tropical cyclone numbers and ACE associated with winter warm and cold years mainly occur in July–October. The results consistently indicate a distinct tendency for increased occurrence of tropical cyclone frequency and intensity in the hurricane season following anomalously warm wintertime SST in the Atlantic MDR.

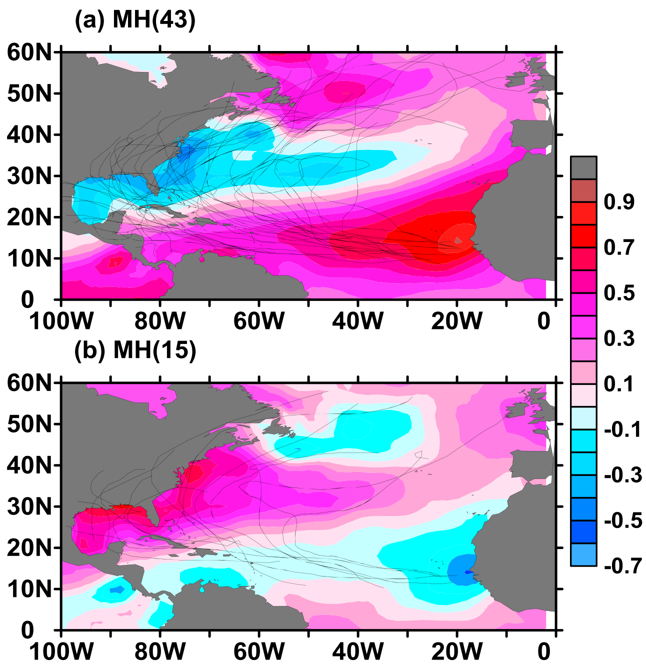

Figure 2. Trajectories of major hurricanes (MH) in the subsequent hurricane season for the years with winter (a) warm and (b) cold SST anomalies (shaded, unit: °C) in the Atlantic MDR during 1950–2010.

Wintertime SST anomalies in the MDR may also affect the genesis locations and tracks of tropical cyclones in the subsequent hurricane season. Figure S3 shows the composite of average track density anomalies relative to the 60 year climatology for the period of 1951–2010. Track locations are binned into 5° × 5° grid boxes to calculate the track density. Track density for either a composite of winter warm or cold year is defined as the number of tropical cyclones passing through each grid box during the JJASON months divided by the total number of years (10 for the warm and cold composites). For winter warm years, track density in the subsequent season is above normal across most of the North Atlantic, with a maximum concentration over the Gulf of Mexico. Compared to the climatology, track density associated with winter cold years is abnormally low over the entire North Atlantic (Figure S3).

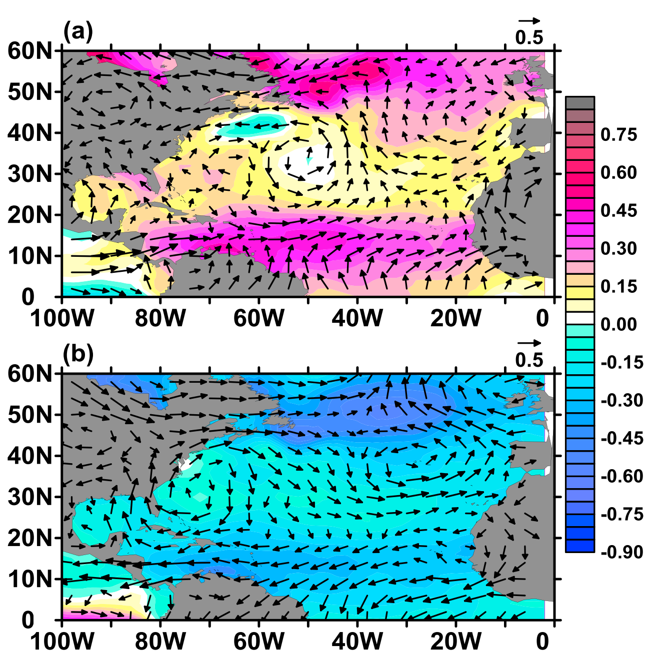

Figure 3. Composites of subsequent hurricane season SST anomalies (shaded, unit: °C) and 925 hPa wind anomalies (vectors, unit: m/s) for (a) the winter warm years and (b) winter cold years during 1951–2010.

4. Possible Mechanisms

Which processes link the preceding winter SST variability to anomalous hurricane activity in the subsequent hurricane season? Figure 3 shows the SST and 925 hPa wind vector anomaly composites in the subsequent hurricane season associated with winter warm and cold years. In the hurricane season associated with the preceding winter warm years, warm SST anomalies nearly cover the whole North Atlantic. Two

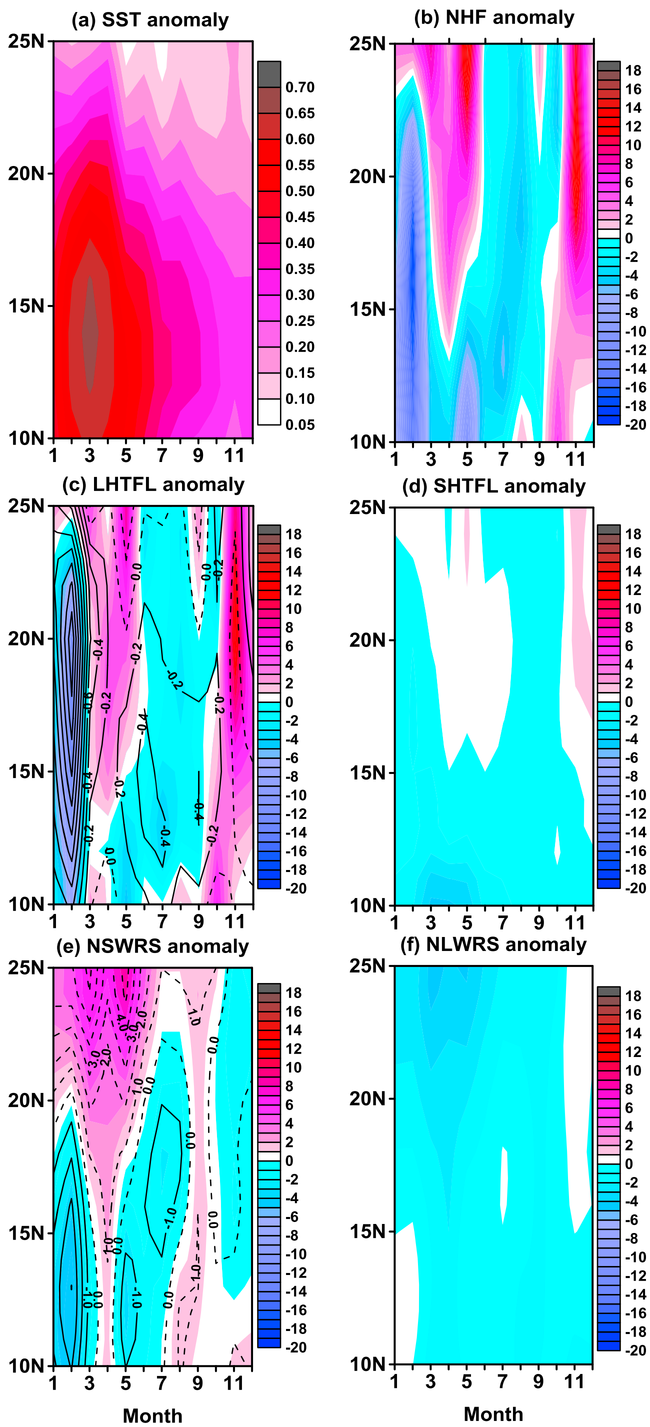

Figure 4. Seasonal evolution of zonally averaged (a) SST (unit: °C), (b) net heat flux (NHF, unit: W/m^2), (c) latent heat flux (LHTFL, unit: W/m^2), (d) sensible heat flux (SHTFL, unit: W/m^2), (e) net shortwave radiation (NSWRS, unit: W/m^2), and (f) net longwave radiation (NLWRS, unit: W/m^2) anomaly composites over the MDR for the winter warm years. Note that the color scales in Figures 4b–4f are the same. Contours in Figures 4c and 4e are wind speed (unit: m/s, contour interval: 0.2) and total cloud cover anomalies (unit: %, contour interval: 1.0), respectively. The dashed and solid contours indicate positive and negative anomalies, respectively. The upward flux is positive.

particularly anomalously warm regions are located in the MDR and from 50°N to 60°N. The 925 hPa trade wind speed is below normal over the MDR (Figure 3). Vertical wind shear is also abnormally low over the MDR (Figure S4). These environment conditions are conducive to an active hurricane season [e.g., *Shapiro and Goldenberg*, 1998; *Foltz and McPhaden*, 2006; *Saunders and Lea*, 2008]. The reverse is true for hurricane seasons associated with the preceding winter cold years (Figure 3).

To further explore the preceding wintertime SST anomalies' control on summer hurricane activity, we examine the seasonal evolution of MDR SST anomalies. As is shown in Figure 4, winter warm SST anomalies mainly result from abnormally low latent heat loss and high downward shortwave radiation, consistent with the case study for the anomalously warm event in 2005 [*Foltz and McPhaden*, 2006]. Anomalously low wind speed and cloud fraction in winter may be responsible for the corresponding decrease in latent heat loss and increase in surface shortwave radiation, respectively (Figures 4c and 4e). Furthermore, the SST warming decreases wind speed, reducing latent heat loss and persisting the SST anomalies into the following hurricane season (Figure 5a), indicative of the positive wind-evaporation-SST feedback process [*Chang et al.*, 1997; *Xie*, 1999]. A previous study also found that low-level cloud cover dominates between 10°N and 20°N and that the ratio of low-level to total cloud cover could exceed 90% [see *Tanimoto and Xie*, 2002, Figures 10b and 12a]. The composites show that the anomalous cloud pattern in the hurricane season is influenced by the preceding winter SST anomalies in the MDR. The reduced cloudiness increases the shortwave radiation flux absorbed by the sea surface throughout the following summer. From June to August, the positive shortwave radiation anomalies of up to 5 Wm^{-2} over the MDR, along with the low latent heat loss, prolong the local SST anomalies

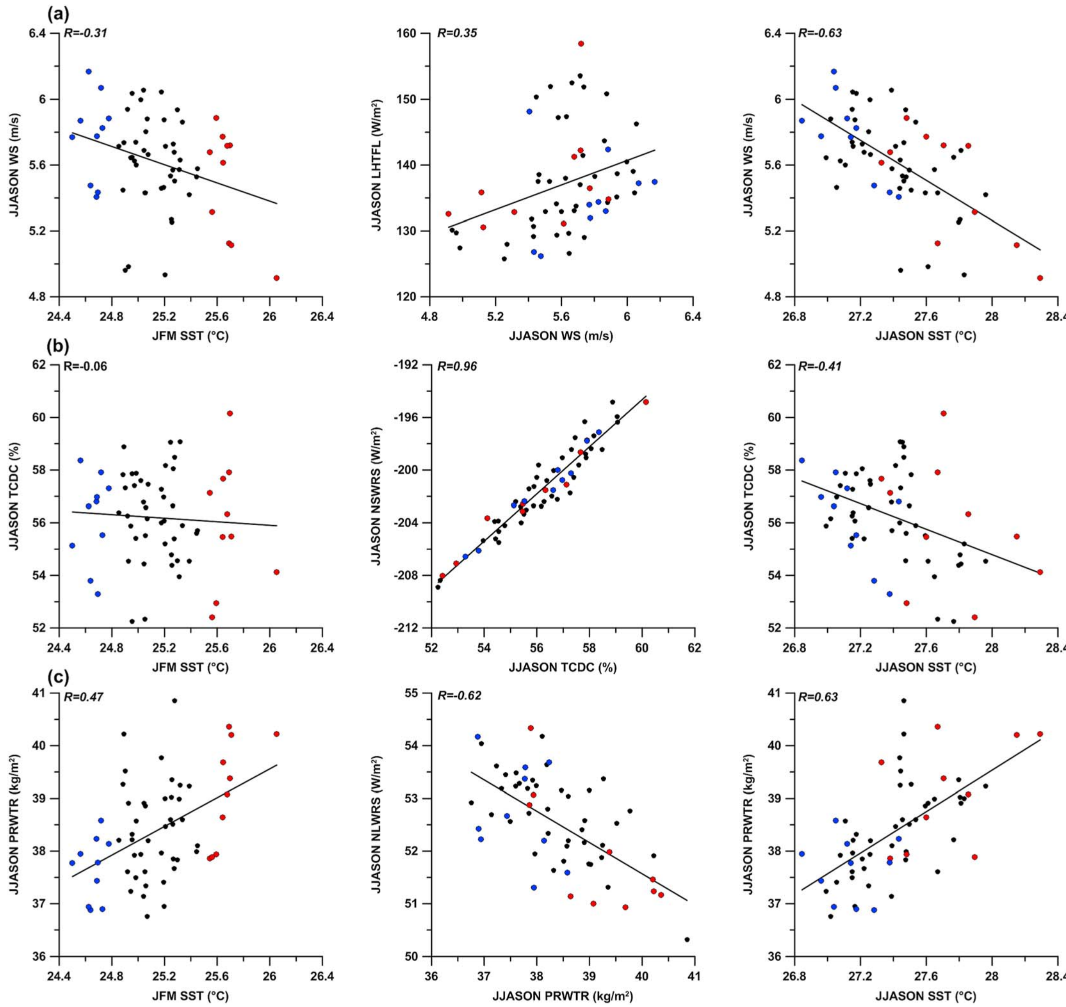

Figure 5. (a) Scatterplots between JFM SST and June–November (JJASON) wind speed (WS), between JJASON WS and JJASON latent heat net flux (LHTFL), and between JJASON SST and JJASON WS during 1951–2010. (b) Scatterplots between JFM SST and JJASON total cloud cover (TCDC), between JJASON TCDC and JJASON net shortwave radiations (NSWRS), and between JJASON SST and JJASON TCDC during 1951–2010. (c) Scatterplots between JFM SST and JJASON precipitable water content (PRWTR), between JJASON PRWTR and JJASON net longwave radiation (NLWRS), and between JJASON SST and JJASON PRWTR during 1951–2010. Italic correlation coefficients are statistically significant at the 95% confidence level. The red and blue dots indicate the values in the 10 winter warm and cold years, respectively.

(Figures 4c and 4e). The increased shortwave radiation implies a positive feedback between the SST anomaly and low cloud over the tropical North Atlantic in boreal summer [*Tanimoto and Xie*, 2002]: namely, when the SST becomes warm in the hurricane season, cloud amounts decrease, leading to more shortwave radiation absorbed by the sea surface and further warming the ocean (Figure 5b). During the boreal spring, it is worth noting that the downward longwave radiation anomaly and low sensible loss may partly offset the damping effect of the upward shortwave radiation anomaly, hence favoring the persistence of the anomalously warm SST (Figures 4d and 4f).

Another potential contributor to the winter SST anomalies' persistence into the hurricane season may be water vapor-SST feedback. As is well known, water vapor is expected to increase with increasing SST [*Shie et al.*, 2006]. Moreover, water vapor is a powerful greenhouse gas and can amplify the initial SST warming by increasing downward longwave radiation. As is shown in Figure 5c, the winter warm SST anomalies enhance atmospheric water vapor, therefore increasing downward longwave radiation to maintain the warm SST anomalies in the hurricane season. Compared with correlations between winter MDR SST and hurricane season wind speed, and between winter MDR SST and total cloud cover in the hurricane season, the correlation between winter MDR SST and water vapor content of the hurricane season is much stronger (Figure 5, left column), indicating an active role of the water vapor-SST feedback in the persistence of the winter warm SST anomalies.

In addition, Figure S5 shows that the seasonal evolution of the MDR SST generally follows the pattern of all-sky downward longwave radiation, whether it is for the winter warm and cold years or the climatological mean. The seasonal correlation ($R > 0.9$) between MDR SST and all-sky downward longwave radiation is significant at the 99.9% confidence level. In contrast, there is no significant relationship (at the 90% confidence level) between the seasonal evolution of MDR SST and that of the longwave cloud forcing component. These results indicate that downward longwave radiation in the clear sky strongly affects seasonal variability of MDR SST, while the longwave component of cloud forcing is less important. It is shown in Figure S5 that the seasonal pattern of water vapor is in good agreement with those of SST and downward longwave radiation. We also find that the correlation ($R = -0.64$) between June–November averaged net longwave radiation and precipitable water content is much stronger than that ($R = -0.28$) between June–November averaged net longwave radiation and total cloud cover during 1951–2010, suggesting that water vapor dominates the variability of longwave radiation flux over the MDR (Figure S6). In summary, it is concluded that the winter warm SST anomalies may enhance atmospheric water vapor content, which in turn increases downward longwave radiation to constrain the seasonal cycle of the SST.

In order to seek a universal relationship, we have not removed trends nor decadal/multidecadal variations from the data when analyzing the mechanisms of winter MDR SST anomalies' persistence. We have found that the persistence of winter MDR SST anomalies may be partly due to these longer period background SST variations (Figure S7). Further analyses that separate the influences of different sources on the winter-summer SST anomalies persistence are necessary to increase our understanding of the wintertime influence on Atlantic hurricane activity.

5. Summary and Discussion

This study investigates the persistent effect of wintertime SST anomalies in the MDR on hurricane activity using observation and reanalysis data. We find that the wintertime SST anomalies of the MDR can persist into the subsequent summer, accounting for 42% of variance of SST in the following hurricane season. Analyses show a distinct tendency for increased occurrence of tropical cyclone frequency and intensity in the hurricane season following anomalously warm wintertime SST in the MDR. It is also indicated that the skill of seasonal hurricane forecasts based on a coupled atmosphere-ocean model will partly depend on the model's ability to predict the seasonal evolution of MDR SST.

The anomalously warm winter SST over the MDR is mainly attributed to anomalously low latent heat loss and high surface solar radiation. The sensible heat flux and the longwave radiation flux provide a secondary contribution to the winter warm SST anomalies. Initial winter warm SST anomalies in the MDR increase water vapor content and in turn enhance the downward longwave radiation flux, which may constrain the seasonal evolution of warm SST over the MDR. Wind speed and cloud cover in the MDR during the subsequent hurricane season decrease in response to the warmer SST, thereby reducing latent heat loss, increasing the radiation flux at the surface and persisting the positive SST anomalies. This study highlights the active role of the water vapor-SST feedback process in the seasonal persistence of the winter MDR SST anomalies. In fact, water vapor-SST, wind-evaporation-SST, and cloud-SST feedback processes involve complex interactions. A previous study has found that cloud cover may modulate the surface radiation flux, acting to amplify the wind-evaporation-SST feedback in the TNA [*Evan et al.*, 2013]. It is difficult to identify the leading role of the above-mentioned three feedback processes in persistence of the winter warm MDR SST anomalies through the linear correlation analysis. It is necessary to evaluate the relative contributions from these feedback processes in an air-sea coupled model in a future study.

SST variability over the TNA has been shown to involve two main remote forcings from El Niño and the North Atlantic Oscillation (NAO) [*Enfield and Mayer*, 1997; *Tanimoto and Xie*, 1999; *Saravanan and Chang*, 2000; *Czaja et al.*, 2002; *Lee et al.*, 2008]. El Niño–Southern Oscillation (ENSO) can induce significant SST warming over the TNA approximately 4–5 months after the mature phase of El Niño events [*Enfield and Mayer*, 1997]. *Czaja et al.* [2002] found that almost all strong SST anomalies in the TNA region from 1950 to 2000 can be explained by the prior ENSO or NAO events. Using a coupled ocean-atmosphere general circulation model, *Huang and Shukla* [2005] suggested that the TNA SST pattern in boreal winter-spring is closely associated with surface heat flux changes due to extratropical atmospheric disturbances forced by the NAO. We also find that four out of 10 winter warm MDR SST anomaly events identified in this study occur in the strong El Niño or negative NAO phase of boreal winter (1958 and 2010, strong El Niño and negative NAO phase; 1969, moderate El Niño and strong negative NAO phase; and 1998, strong El Niño). Because SST over the TNA is strongly influenced by ENSO and NAO, the observed three feedback processes in this study may involve the remote ENSO and NAO influences. In addition, we find that decadal variability of MDR SST contributes significantly to the observed persistence from winter to the hurricane season. Quantification of the influences of ENSO, NAO, and tropical Atlantic decadal variability on the persistence of wintertime SST into the hurricane season remains an important topic for further research.

Acknowledgments
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References

Alexander, M. A., and C. Deser (1995), A mechanism for the recurrence of wintertime midlatitude SST anomalies, *J. Phys. Oceanogr.*, *25*, 122–137.

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

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.

Czaja, A., P. van der Vaart, and J. Marshall (2002), A diagnostic study of the role of remote forcing in tropical Atlantic variability, *J. Clim.*, *15*, 3280–3290.

Elsner, J. B., R. J. Murnane, and T. H. Jagger (2006), Forecasting U.S. hurricanes 6 months in advance, *Geophys. Res. Lett.*, *33*, L10704, doi:10.1029/2006GL025693.

Emanuel, K. A. (1999), Thermodynamic control of hurricane intensity, *Nature*, *401*, 665–669, doi:10.1002/2016GL069961.

Emanuel, K. A. (2001), Contribution of tropical cyclone to meridional heat transport by the oceans, *J. Geophys. Res.*, *106*(D14), 14771–14781.

Emanuel, K. A. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686–688.

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*(C1), 929–945.

Evan, A. T., A. J. Allan, R. Bennartz, and D. J. Vimont (2013), The modification of sea surface temperature anomaly linear damping time scales by stratocumulus clouds, *J. Climate.*, *26*, 3619–3630.

Fedorov, A. V., C. M. Brierley, and K. A. Emanuel (2010), Tropical cyclones and permanent El Niño in the early Pliocene epoch, *Nature*, *463*(7284), 1066–1070.

Foltz, G. R., and M. J. McPhaden (2006), Unusually warm sea surface temperatures in the tropical North Atlantic during 2005, *Geophys. Res. Lett.*, *33*, L19703, doi:10.1029/2006GL027394.

Foltz, G. R., S. A. Grodsky, J. A. Carton, and M. J. McPhaden (2003), Seasonal mixed layer heat budget of the tropical Atlantic Ocean, *J. Geophys. Res.*, *108*(C5), 3146, doi:10.1029/2002JC001584.

Goldenberg, S. B., and L. J. Shapiro (1996), Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricanes, *J. Clim.*, *9*, 1169–1187.

Goldenberg, S. B., 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.

Hoyos, C. D., P. A. Agudelo, P. Webster, and J. A. Curry (2006), Deconvolution of the factors contributing to the increase in global hurricane intensity, *Science*, *312*, 94–97.

Hu, A., and G. A. Meehl (2009), Effect of the Atlantic hurricanes on the oceanic meridional overturning circulation and heat transport, *Geophys. Res. Lett.*, *36*, L03702, doi:10.1029/2008GL036680.

Huang, B., and J. J. Shukla (2005), Ocean–atmosphere interactions in the tropical and subtropical Atlantic Ocean, *J. Clim.*, *18*, 1652–1672, doi:10.1175/JCLI3368.1.

Jansen, M., and R. Ferrari (2009), Impact of the latitudinal distribution of tropical cyclones on ocean heat transport, *Geophys. Res. Lett.*, *36*, L06604, doi:10.1029/2008GL036796.

Jansen, M., R. Ferrari, and T. A. Mooring (2010), Seasonal versus permanent thermocline warming by tropical cyclones, *Geophys. Res. Lett.*, *37*, L03602, doi:10.1029/2009GL041808.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-Year Reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Klotzbach, P. J. (2006), Trends in global tropical cyclone activity over the past twenty years (1986–2005), *Geophys. Res. Lett.*, *33*, L10805, doi:10.1029/2006GL025881.

Klotzbach, P. J., W. M. Gray, and C. T. Fogarty (2015), Active Atlantic hurricane era at its end?, *Nat. Geosci.*, *8*, 737–738, doi:10.1038/ngeo2529.

Knabb, R. D., J. R. Rhome, and D. P. Brown (2005), Hurricane Katrina: August 23–30, 2005, National Hurricane Center Tropical Cyclone Report, 20 Dec.

Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann (2010), The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data, *Bull. Am. Meteorol. Soc.*, *91*, 363–376, doi:10.1175/2009BAMS2755.1.

Korty, R. L., K. A. Emanuel, and J. R. Scott (2008), Tropical cyclone-induced upper-ocean mixing and climate: Application to equable climates, *J. Clim.*, *21*(4), 638–654.

Landsea, C., and J. L. Franklin (2013), Atlantic hurricane database uncertainty and presentation of a new database format, *Mon. Wea. Rev.*, *141*, 3576–3359.

Landsea, C. W., R. A. Pielke Jr., A. M. Mestas-Nuñez, and J. A. Knaff (1999), Atlantic basin hurricanes: Indices of climate changes, *Clim. Change*, *42*, 89–129.

Lee, S.-K., D. B. Enfield, and C. Wang (2008), Why do some El Ninos have no impact on tropical North Atlantic SST?, *Geophys. Res. Lett.*, *35*, L16705, doi:10.1029/2008GL034734.

Mann, M. E., and K. A. Emanuel (2006), Atlantic hurricane trends linked to climate change, *Eos Trans. AGU*, *87*, 233–244.

Medhaug, I., and T. Furevik (2011), North Atlantic 20th century multidecadal variability in coupled climate models: Sea surface temperature and ocean overturning circulation, *Ocean Sci.*, *7*, 389–404.

Mei, W., F. Primeau, J. C. McWilliams, and C. Pasquero (2013), Sea surface height evidence for long-term warming effects of tropical cyclones on the ocean, *Proc. Natl. Acad. Sci. U.S.A.*, *110*(38), 15207–15210.

Pasquero, C., and K. Emanuel (2008), Tropical cyclones and transient upper-ocean warming, *J. Clim.*, *21*(1), 149–162.

Quenouille, M. H. (1952), *Associated Measurements*, 242 pp., Butterworths Sci. Publ., London.

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

Saunders, M. A., and S. A. Lea (2008), Large contribution of sea surface warming to recent increase in Atlantic hurricane activity, *Nature*, *451*(7178), 557–560, doi:10.1038/nature06422.

Shapiro, L. J., and S. B. Goldenberg (1998), Atlantic sea surface temperatures and tropical cyclone formation, *J. Clim.*, *11*, 578–590.

Shie, C. L., W. K. Tao, and J. Simpson (2006), A note on the relationship between temperature and water vapor over oceans, including sea surface temperature effects, *Adv. Atmos. Sci.*, *23*, 141–148.

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

Sriver, R. L., and M. Huber (2007), Observational evidence for an ocean heat pump induced by tropical cyclones, *Nature*, *447*(7144), 577–580.

Tanimoto, Y., and S.-P. Xie, (1999), Ocean-Atmosphere Variability over the Pan-Atlantic basin, *J. Meteorol. Soc. Jpn.*, *77*, 31–46.

Tanimoto, Y., and S. P. Xie (2002), Inter-hemispheric decadal variations in SST, surface wind, heat flux and cloud cover over the Atlantic Ocean, *J. Meteorol. Soc. Jpn.*, *80*(5), 1199–1219.

Trenberth, K. E., and D. J. Shea (2006), Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, *33*, L12704, doi:10.1029/2006GL026894.

Wang, X. D., C. Wang, G. J. Han, W. Li, and X. R. Wu (2014), Effects of tropical cyclones on large-scale circulation and ocean heat transport in the South China Sea, *Clim. Dyn.*, *43*(12), 3351–3366.

Wang, C., S. Dong, A. T. Evan, G. R. Foltz, and S.-K. Lee (2012), Multidecadal covariability of North Atlantic sea surface temperature, African dust, Sahel rainfall and Atlantic hurricanes, *J. Clim.*, *25*, 5404–5415.

Wang, C., X. D. Wang, R. H. Weisberg, and M. L. Black (2017), Variability of tropical cyclone rapid intensification in the North Atlantic and its relationship with climate variations, *Clim. Dyn.*, doi:10.1007/s00382-017-3537-9.

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.

Xie, S. P. (1999), A dynamic ocean–atmosphere model of the tropical Atlantic decadal variability, *J. Clim.*, *12*, 64–70.

Yu, L., X. Jin, and R. A. Weller (2006), Role of net surface heat flux in the seasonal evolution of sea surface temperature in the Atlantic Ocean, *J. Clim.*, *9*, 6153–6169.

Zhang, R., and T. L. Delworth (2006), Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, *Geophys. Res. Lett.*, *33*, L17712, doi:10.1029/2006GL026267.