Persistent Atmospheric and Oceanic Anomalies in the North Atlantic from Summer 2009 to Summer 2010

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(Manuscript received 19 November 2010, in final form 14 March 2011)

ABSTRACT

In this work, the authors analyze the air–sea interaction processes associated with the persistent atmospheric and oceanic anomalies in the North Atlantic Ocean during summer 2009–summer 2010 with a record-breaking positive sea surface temperature anomaly (SSTA) in the hurricane Main Development Region (MDR) in the spring and summer of 2010. Contributions to the anomalies from the El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and a long-term trend are identified. The warming in the tropical North Atlantic during summer 2009–summer 2010 represented a typical response to ENSO, preconditioned and *amplified* by the influence of a strong and persistent negative phase of the NAO. The long-term trends enhanced the warming in the high and low latitudes and weakened the cooling in the midlatitudes. The persistent negative phase of the NAO was associated with active thermodynamic air–sea interaction in the North Atlantic basin. Surface wind anomalies associated with the NAO altered the ocean surface heat flux and changed the SSTA, which was likely further enhanced by the positive wind speed–evaporation–SST feedback. The total heat flux was dominated by the latent and sensible heat fluxes, while the shortwave radiation contributed to the tropical SSTA to a lesser degree. Sensitivity experiments with an atmospheric general circulation model forced by observed SST in the Atlantic Ocean alone suggested that the Atlantic SSTA, which was partly forced by the NAO, had some positive contribution to the persistence of the negative phase of the NAO. Therefore, the persistent NAO condition is partly an outcome of the global climate anomalies and the ocean–atmosphere feedback within the Atlantic basin. The combination of the ENSO, NAO, and long-term trend resulted in the record-breaking positive SSTA in the MDR in the boreal spring and summer of 2010. On the basis of the statistical relationship, the SSTA pattern in the North Atlantic was reasonably well predicted by using the preceding ENSO and NAO as predictors.

1. Introduction

During the period from the summer of 2009 to the summer of 2010, a strong warming tendency of sea surface temperature (SST) occurred in the tropical and subtropical North Atlantic Ocean (Fig. 1a), ending with a record-breaking SST anomaly (SSTA) for several months in the hurricane Main Development Region (MDR: 10°–20°N, 20°–85°W; see the rectangular box in Fig. 2f). The SSTA in the MDR reached 0.94°C for the mean from June to August (JJA) 2010 and was a record value since 1950 (Fig. 1b), which partly set the background for the active hurricane season in 2010.

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DOI: 10.1175/2011JCLI4213.1

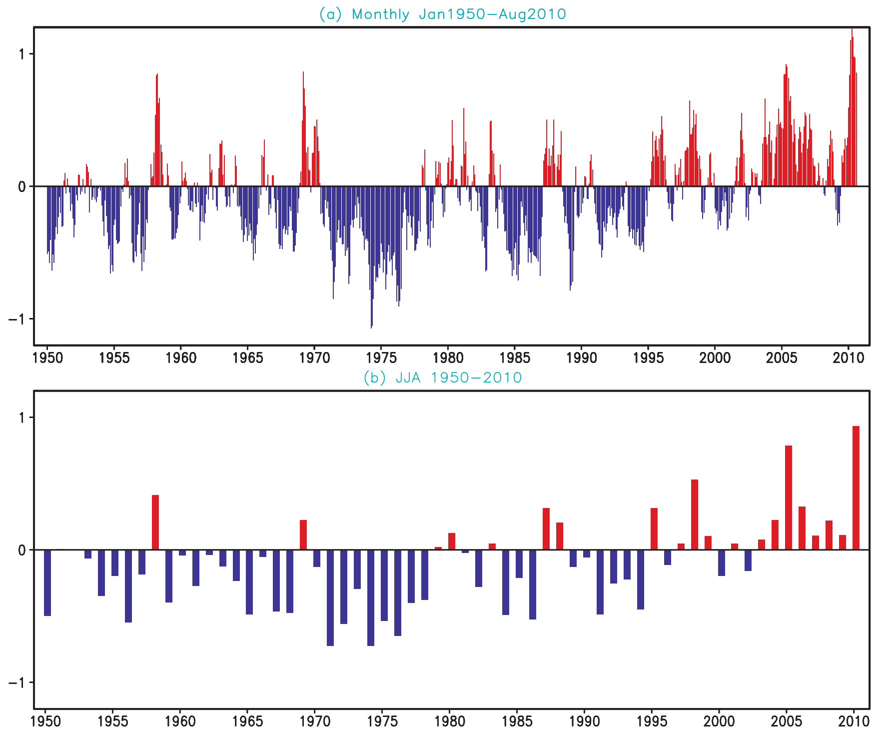

FIG. 1. (top) Monthly mean SSTA averaged within the hurricane MDR (10°–20°N, 20°–85°W) in the tropical North Atlantic during January 1950–August 2010 and (bottom) the JJA SSTA averaged in the MDR during 1950–2010. The anomalies are computed on the basis of the climatology in 1979–2009; the data are ERSSTv3b.

In conjunction with these record-breaking SSTAs in the North Atlantic during this period, the phase of the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO) (Hurrell 1995; Wallace 2000) was exceptionally negative for most of these months (L'Heureux et al. 2010; Wang et al. 2010; Cohen et al. 2010; Seager et al. 2010), and a strong El Niño also developed in the tropical Pacific Ocean (Xue et al. 2010). Furthermore, the long persistent negative phase of the NAO and the anomalous atmospheric circulation in the Northern Hemisphere (NH) associated with the El Niño were the leading factors causing below-normal temperature and precipitation fluctuations over the eastern part of North America and parts of Eurasia during 2009–10 (Wang et al. 2010; L'Heureux et al. 2010; Seager et al. 2010). This attribution was consistent with the long-term statistical relation of the NAO and ENSO with climate variability in the NH (Hurrell 1995; Diaz et al. 2001; Thompson and Wallace 2001; Marshall et al. 2001; Wu et al. 2004; Hurrell et al. 2003; references therein). Given the existence of these extreme anomalies in the various components of the climate system, it is of interest to examine evolution of the atmosphere and ocean anomalies in the North Atlantic during 2009–10, to investigate the local air–sea interaction processes, and to identify the contributions from the El Niño, NAO, and long-term trends.

Climate anomalies in the tropical and extratropical North Atlantic can be generated by both local air–sea interaction and remote influences (Curtis and Hastenrath 1995; Enfield and Mayer 1997; Chang et al. 1997, 2003, 2006; Seager et al. 2000; Giannini et al. 2001; Marshall et al. 2001; Chiang et al. 2002; Huang et al. 2002; Hurrell et al. 2003; Thompson et al. 2003; Visbeck et al. 2003; Wu et al. 2004; Huang 2004; Xie and Carton 2004; Hu and Huang 2006a,b, 2007a; Muñoz et al. 2010). A major process of the air–sea interaction is the thermodynamic feedback between the ocean and the atmosphere on seasonal-to-interannual time scales. In particular, ocean surface wind anomalies associated with atmospheric circulation anomalies, such as the NAO, alter ocean surface evaporative heat fluxes and change SST efficiently and may be the dominant cause for SST fluctuations in the North Atlantic Ocean. For example, by simulating the ocean response to historical atmospheric forcing, Seager et al. (2000) found that almost all of the variability of the North Atlantic SST during 1958–98 can be explained as a response to changes in surface fluxes caused by changes in the atmospheric circulation, particularly in association

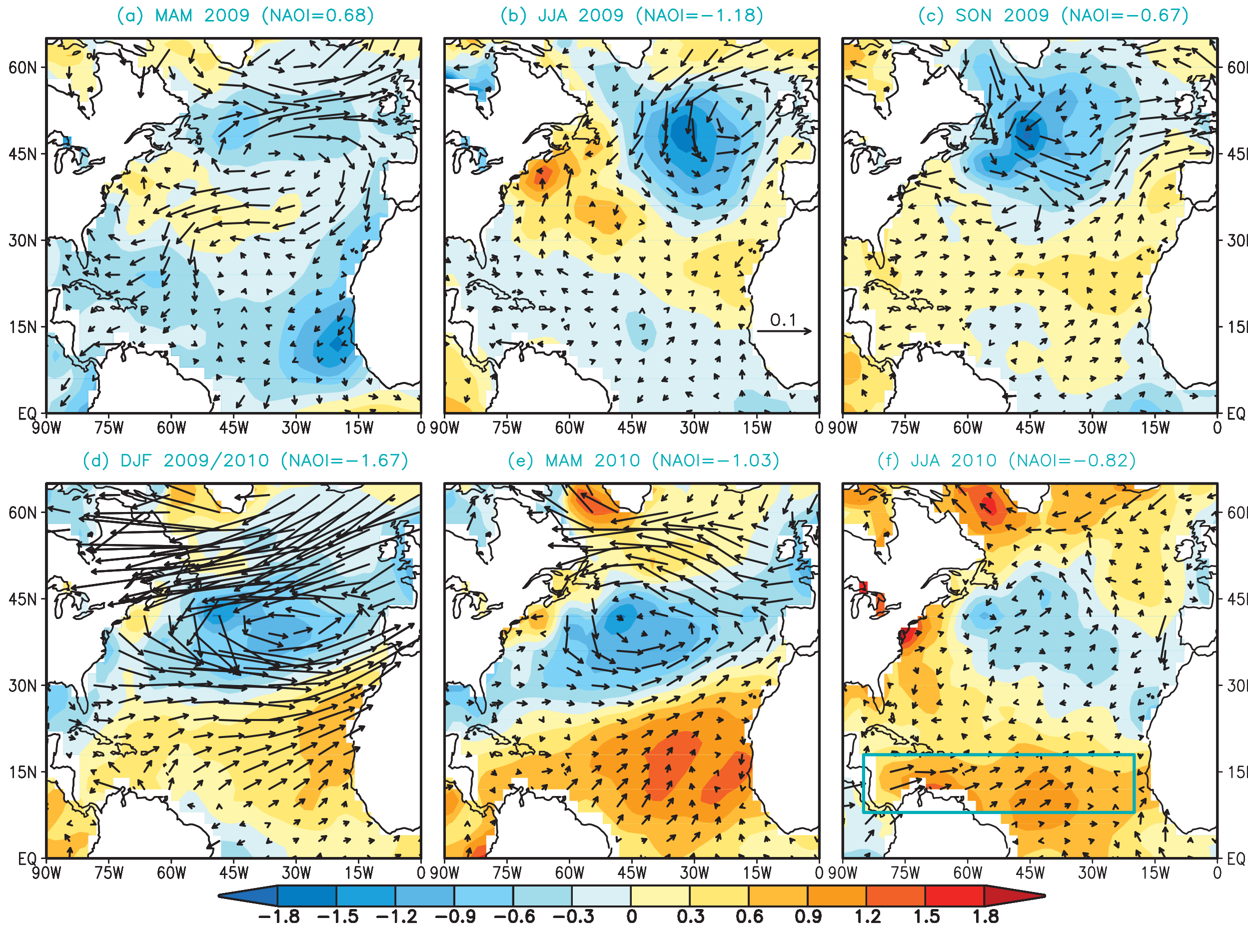

FIG. 2. Seasonal mean SST (°C; shading) and surface wind stress (N m^{-2}; vector) anomalies during MAM 2009–JJA 2010. The rectangle in (f) is the hurricane MDR (10°–20°N, 20°–85°W), and values of the NAO index are listed at the top of each panel. Both SSTA and wind stress anomalies were detrended.

with the NAO. Czaja et al. (2002) also showed that the SST variability on interannual to interdecadal time scales can be largely explained as a result of direct atmospheric forcing. Analysis also indicated that nearly half of the SST variability at interannual and decadal time scales is a manifestation of coupled variability in the tropical Atlantic climate system alone, with regional ocean–atmosphere coupling playing a critical role (Liu et al. 2004).

More importantly, a positive feedback among the surface wind, evaporation, and SST through coupling between the lower atmosphere and the oceanic mixed layer plays a key role in generating SSTA in the tropical and subtropical Atlantic Ocean. This wind–evaporation–SST (WES) feedback not only refers to the forcing of SSTAs by the atmosphere as a result from changing wind speeds (which in turn locally affects air–sea fluxes and SST), but also includes a circulation response of the atmosphere through SST-induced anomalous sea level pressure gradients, as well as atmospheric convection through a feedback loop. As a result, the circulation response of the atmosphere may also generate a cross-equatorial wind anomaly that changes the SST elsewhere (Saravanan and Chang 2004). Thus, the WES is essentially a nonlocal interaction and has been posited to play an important role in the SST variability in the tropical–subtropical Atlantic Ocean (e.g., Xie and Philander 1994; Chang et al. 1997; Xie 1999; Seager et al. 2000; Huang and Shukla 2005; Mahajan et al. 2010).

The other important influence on the climate anomalies in the tropical and subtropical North Atlantic is from the Pacific ENSO (Curtis and Hastenrath 1995; Enfield and Mayer 1997; Chang et al. 1997, 2003, 2006; Giannini et al. 2001; Chiang et al. 2002; Huang et al. 2002; Huang 2004; Muñoz et al. 2010; Mahajan et al. 2010). For example, Liu et al. (2004) suggested that the remote impact, largely due to ENSO, may contribute to nearly a half of the total variance of the tropical Atlantic SST variability at interannual and decadal time scales.

Enfield and Mayer (1997) found that the major region affected by ENSO is the North Atlantic area of northeast trades west of 40°W along 10°–20°N extending into the Caribbean Sea. In this region, the peak Atlantic warming is usually observed in subsequent springs, 4–5 months after the mature phase of Pacific warm events. They further suggested that the Atlantic warming occurs as a result of the ENSO-induced relaxation in the surface northeast trades, which in turn reduce latent and sensible heat loss from the ocean. This remote forcing also triggers a local WES feedback, which makes the air–sea anomalies more sustainable and persistent through local air–sea interaction. Overall, previous investigations have demonstrated that the ENSO influence on the North Atlantic is through a (Pacific–North American) PNA-like teleconnection pattern and mainly affects the tropical and subtropical Atlantic Ocean through the thermodynamic processes with a lag of about 1–3 seasons. The ENSO impact is also a major external source of a predictable signal at seasonal time scales in the region (Kushnir et al. 2006; Hu and Huang 2007b).

It has also been argued that the SSTA in the North Atlantic can feed back to the atmospheric circulation anomalies at low frequencies (Barsugli and Battisti 1998; Czaja and Frankignoul 1999, 2002; Kushnir et al. 2002; Peng et al. 2003; Cassou et al. 2004), although the intensity of the SST feedback on the atmospheric variability, especially in the extratropics, remains a matter of debate (Peng et al. 2005). Recently, Zhang et al. (2010) estimated that about 12% of the NAO variability may be in response to oceanic processes in their coupled data assimilation system. Czaja and Frankignoul (2002) pointed out statistically significant covariances when SST leads geopotential height at 500 hPa (H_{500}) in the North Atlantic on a seasonal time scale. They found a Pan–Atlantic SST pattern precedes the NAO anomalies in the subsequent winter by up to six months. The mechanism for the feedback is reasoned to be reduced surface thermal damping due to the coupled adjustment of the air–sea temperature difference (Kushnir et al. 2002). As a consequence, greater and longer persisting thermal anomalies are formed in the coupled atmosphere–ocean system compared to the uncoupled one (Barsugli and Battisti 1998). This SST feedback on the atmospheric variability is put forward as one of the local sources for the possibility of skillful prediction of the NAO at interseasonal and longer time scales (Rodwell et al. 1999; Saunders and Qian 2002; Czaja and Frankignoul 2002; Rodwell 2003).

Actually, the air–sea feedback is not confined in local feedback. Previous studies have suggested that the tropical and subtropical portion of the tripole pattern of the North Atlantic SSTA are responsible for forcing part of the NAO variability (Mehta 1998; Watanabe and Kimoto 1999; Rodwell et al. 1999; Robertson et al. 2000; Okumura et al. 2001; Cassou and Terray 2001). Experiments using an atmospheric general circulation model (AGCM) forced by the North Atlantic SSTA tripole pattern showed an NAO-like dipole response over the Atlantic, and was mainly due to a wave train forced by the tropical lobe of the SSTA tripole (Peng et al. 2003). On the other hand, some investigations suggested that the SST feedback may not be as important to either the atmosphere or the ocean, and the mechanisms of the observed SST–NAO connections have not been fully understood. For instance, Peng et al. (2005) using AGCM experiments indicated that the response of atmospheric circulation to the North Atlantic horseshoe pattern of SSTA may have little projection onto the NAO pattern. Therefore, the SST forcing to the NAO with a 6-month lead cannot be explained by the directly forced planetary waves.

Although the role of air–sea feedback on the midlatitude low-frequency climate variation is still not clear, some studies (e.g., Xie 1999; Huang and Shukla 2005) have demonstrated that the WES feedback plays a major role in expanding the SSTA forced by extratropical wind fluctuations into the subtropical and tropical Atlantic as a source of the tropical variability. Moreover, as we discussed above, several processes (e.g., ENSO remote impact and NAO-associated Atlantic air–sea interaction) influence the tropical Atlantic SST variations with comparable strengths. Therefore, the interferences and interactions of these processes play a major role in shaping the SSTA strength and pattern. That may explain the fact that the tropical Atlantic SSTA, though usually maintained at a moderate level, can reach intensive strength occasionally.

To better quantify the roles of various processes, including the influence of remote and local atmospheric variability on the evolution of SSTA in the North Atlantic, in this study we analyze the premise that the record-breaking SSTA in the tropical–subtropical Atlantic Ocean during 2009–10 was a consequence of the oceanic response to the combinative forcing of the persistent negative NAO, the El Niño event, and the long-term trend. Also, by analyzing AGCM simulations forced by the observed regional SSTAs, we examine the possible contribution of Atlantic SST feedback on the persistence of the atmospheric and oceanic anomalies in the North Atlantic during the period. Furthermore, we explore the potential application of the current results in the SST prediction over the North Atlantic.

The paper is organized as follows. After describing the data and model experiments used in this work in section 2, we discuss the evolution of the atmosphere and ocean surface climate anomalies and the associated air–sea interaction in section 3. In section 4, we examine the historical connection between the North Atlantic climate variability with the NAO and ENSO and explore the possible prediction aspects for SSTA and hurricane activities in the North Atlantic. The possible connection of the SST anomalies with the long-term variation of SST and ocean surface wind stress is also discussed. A summary with some discussion is given in section 5.

2. Data and model experiments

The data used in this work are mainly from National Centers for Environmental Prediction (NCEP) and U.S. Department of Energy atmospheric reanalysis 2 (R2) (Kanamitsu et al. 2002a) and monthly oceanic analysis from the Global Ocean Data Assimilation System (GODAS) (Behringer and Xue 2004). In GODAS, observed oceanic surface and subsurface temperatures, as well as sea surface heights, are assimilated into the Geophysical Fluid Dynamics Laboratory Modular Ocean Model, version 3 (MOM3), in a domain of the global ocean within 75°S–65°N with a three-dimensional variational data assimilation (3D-VAR) scheme (Behringer et al. 1998). The model has 40 vertical levels with 10-m resolution in the upper 200 m. The horizontal resolution is 1° by 1° with a meridional resolution of ⅓° within 10° of the equator. At the ocean surface the model is forced by the momentum flux, heat flux, and freshwater flux from R2 (Kanamitsu et al. 2002a). Readers can refer to Behringer and Xue (2004) for more details about GODAS. The variables used in this analysis include surface wind stress from GODAS and total heat flux and its components from R2 on a $2° \times 2°$ resolution.

In addition, SST used in this work is from the version 3b of the extended reconstruction of the SST analyses (ERSSTv3b) on a $2° \times 2°$ grid over the period January 1950–August 2010 (Smith et al. 2008). The monthly mean Niño-3.4 index is available from the Climate Prediction Center (CPC) Web page (at http://www.cpc.ncep.noaa.gov/data/indices/nino34.mth.ascii.txt), which is the SSTA averaged in 5°S–5°N, 120°–170°W based on the ERSSTv3b SST. The monthly mean NAO index is also available from the CPC Web page (http://www.cpc.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table), which was calculated on the basis of the first rotated principal component analysis of monthly standardized H_{500} anomaly obtained from the NCEP–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) in the region 20°–90°N between January 1950 and August 2010. We note that the loading pattern is varied with seasons in the NAO index calculation. All anomalies are relative to their monthly mean climatologies averaged for January 1979–December 2009.

To examine the feedback of SST a suite of AGCM simulations are conducted and examined to evaluate the Atlantic SST feedback on the persistent atmospheric circulation anomalies in the North Atlantic. The AGCM is the NCEP Global Forecast System (GFS) (Kanamitsu et al. 2002b), which is the atmospheric component of the NCEP Climate Forecast System (Saha et al. 2006). The horizontal resolution of the model is T62 and has 64 unequally spaced sigma levels. The experiment is forced by observed SST in the Atlantic Ocean from 30°S northward and climatology SST elsewhere. Sea ice in the North Atlantic was specified as observed. Nine ensemble number integrations with slightly different initial conditions are carried out and the integrations are from January 2009 to August 2010. The anomalies are computed as the departure from monthly mean climatology of a 35-yr integration of the GFS forced by global climatological SST. The ensemble mean anomalies of H_{500} and surface wind at 10 m are examined here.

3. Atmospheric and oceanic anomalies and air–sea interaction

a. *Evolution of the atmospheric and oceanic anomalies and thermodynamical processes*

The atmospheric and oceanic anomalies in the North Atlantic evolved coherently during 2009–10 (Fig. 2). The SSTA in the high latitudes was negative in March–May (MAM) 2009 (Fig. 2a). The negative SSTA strengthened significantly in JJA 2009 (Fig. 2b), probably due to a shallower mixed layer in the boreal summer. The SSTA in the North Atlantic was persistent with positive anomalies in high and low latitudes and negative anomalies in midlatitudes during JJA 2009–JJA 2010 (Figs. 2b–f). In JJA and September–October–November (SON) 2009 (Figs. 2b,c), the pattern of SSTA bore some resemblance to the "horseshoe" pattern, with cold SSTA east or southeast of Newfoundland and warm SSTA wrapping around the cold SSTA, mostly from the northeast and southeast (Czaja and Frankignoul 1999, 2002). However, as compared with the typical horseshoe pattern (Czaja and Frankignoul 2002), the negative center was displaced northeastward in JJA 2009 (Fig. 2b), the positive center was absent in high latitudes in SON 2009 (Fig. 2c), and the positive anomalies were confined north of 20°N in JJA 2009 (Fig. 2b). The SSTA distribution evolved to a "tripole like" pattern in December–February (DJF) 2009/10 and MAM 2010 (Figs. 2d,e), when the negative SSTA temporarily extended eastward to the European coast around 45°N. Meanwhile, the positive SSTA in the tropical North Atlantic increased gradually from boreal summer to winter and reached their peak in MAM 2010,

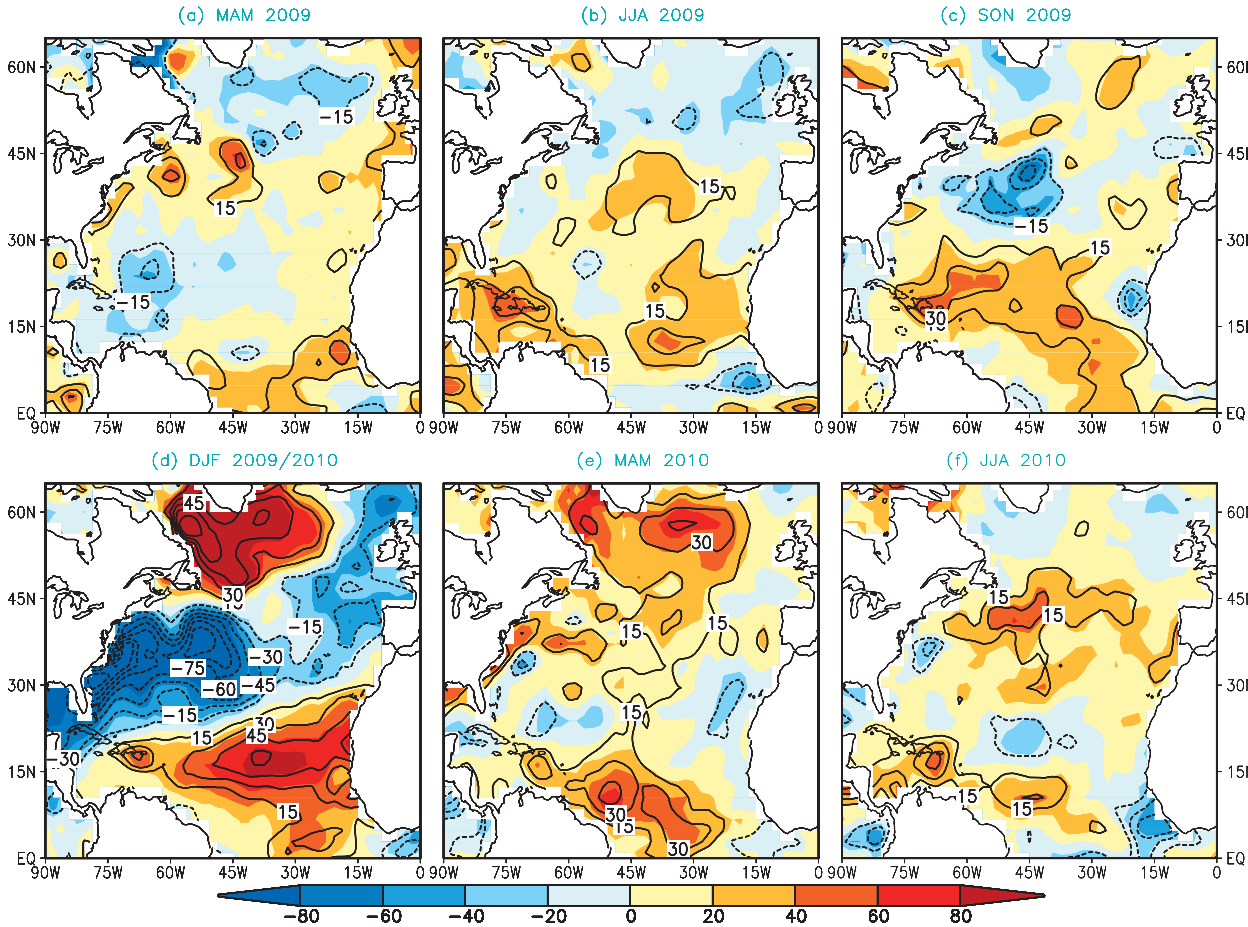

FIG. 3. Seasonal mean total (shading) and latent (contour) heat flux anomalies (W m^{-2}) during MAM 2009–JJA 2010. Positive (negative) is downward (upward), contour interval is 15 W m^{-2}, and the zero line is suppressed. Both total and latent heat flux anomalies were detrended.

likely partly due to the remote influence of the 2009–10 ENSO event that developed in the tropical Pacific (Xue et al. 2010), and will be discussed in the next section.

The evolution of SSTA was associated with the anomalous surface heat flux (Fig. 3). For example, the enhancement of the negative SSTA in the midlatitude (the positive SSTA in the low latitudes) during JJA 2009–MAM 2010 was largely the result of local negative (positive) heat flux anomaly. The consistency of the SSTA evolution with heat flux anomaly suggests an important contribution of the heat flux to the SSTA evolution. Further, the heat flux anomaly itself was largely determined by surface wind anomaly and the phase of the NAO. The persistent anomalous cyclonic circulation is associated with the persistent negative phase of the NAO (see the NAO values in Figs. 2 and 4a). In addition, the anomalous atmospheric cyclone over the North Atlantic generated anomalous upwelling around its center and may be another factor to result in the persistent cold SSTA in midlatitudes (Figs. 2b–e).

The persistent cyclonic surface circulation anomaly over the North Atlantic from JJA 2009 (Fig. 2b) to at least MAM 2010 (Fig. 2e) alters the climatological seasonal circulation and results in the surface wind speed changes (Fig. 4c). The wind speed change, in turn, affects evaporation at the ocean surface. The enhanced (suppressed) evaporation generates anomalous cooling (warming) of the SST by modulating evaporative heat loss from the ocean (Fig. 3), consistent with the WES mechanism (Xie and Philander 1994; Chang et al. 1997). Furthermore, reduced thermal damping between the atmosphere and ocean due to the air–sea coupling may also contribute to the long persistency of the ocean–atmosphere anomalies (Barsugli and Battisti 1998). Moreover, the latent heat flux is about two-thirds of the total heat flux and they also have a similar spatial pattern (Fig. 3), implying that the total heat flux anomaly is dominated by the latent heat flux component. From JJA 2009 to DJF 2009/10 the collocation of SST variation, the wind speed and total heat

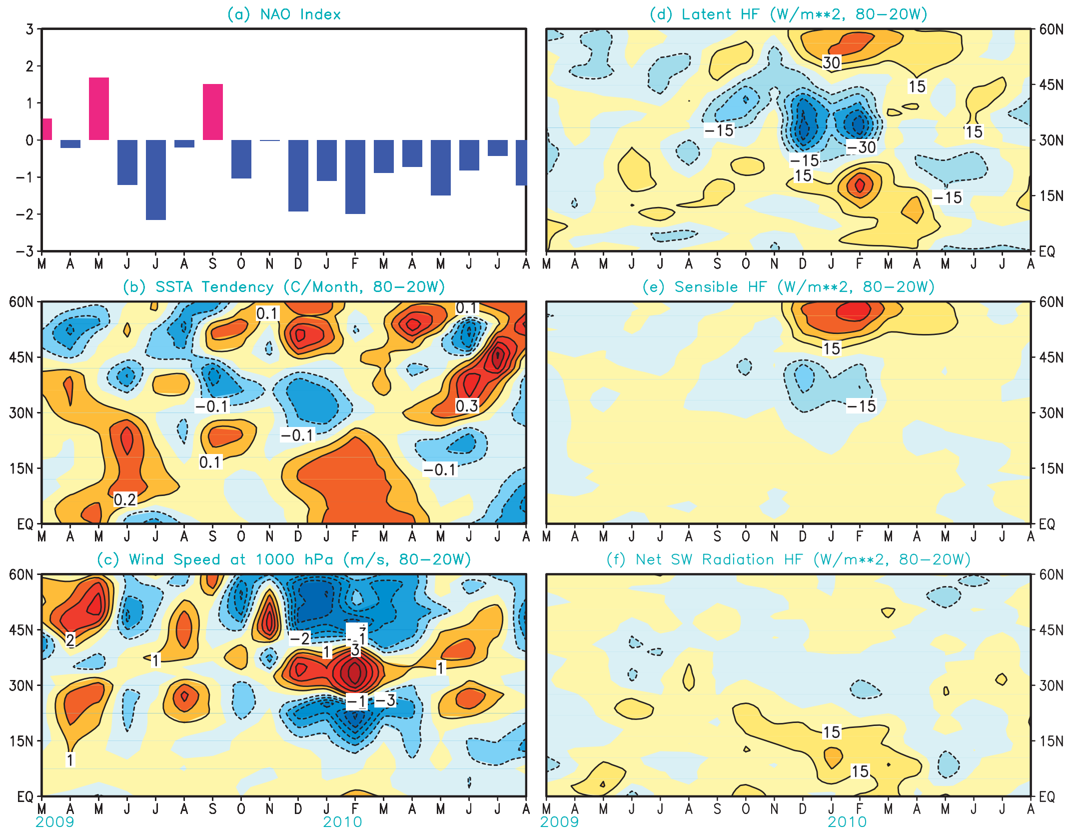

FIG. 4. Monthly mean (a) NAO index, (b) SSTA tendency, (c) wind speed anomalies at 1000 hPa, (d) latent heat flux anomalies, (e) sensible heat flux anomalies, and (f) net shortwave radiation flux anomalies during March 2009–August 2010. In (b)–(f) the zonal average is from 80° to 20°W. The SSTA tendency is defined as the centered difference of the SSTA. Contour intervals are 0.1°C month^{-1} for the SSTA tendency, 1 m s^{-1} for the wind speed, and 15 W m^{-2} for the heat flux. The heat flux is positive (negative) for downward (upward), and the zero contour line is suppressed.

flux anomalies increased, and both negative and positive anomalies of the wind speed and total heat flux intensified, reflecting the seasonality of atmospheric forcing (Portis et al. 2001; Hurrell and Deser 2009). The southward displacement of the atmospheric cyclone from boreal fall to winter follows the seasonal migration of the midlatitude westerlies and the subtropical high in the North Atlantic. This displacement may also be partly prompted by the warm SSTA generated by the westerly anomalies at its southern flank of the subtropical high, which in turn induces warm SSTA farther south, as the WES mechanism would predict. After reaching their maxima in DJF 2009/10 (Figs. 2d and 3d), both amplitudes of the surface wind stress and total heat flux anomalies decreased gradually in the following seasons (Figs. 2e,f, and 3e,f), consist with the seasonality of atmospheric forcing.

To further characterize the evolution of the atmospheric and oceanic anomalies, Fig. 4 shows the NAO index and the time evolution of zonally averaged anomalies of some variables in the North Atlantic during March 2009–August 2010. The negative phase of the NAO corresponds to the negative anomaly of wind speed at 1000 hPa in low and high latitudes and a positive one in midlatitudes (Figs. 4a,c), and is accompanied by a positive (negative) SST tendency in low and high latitudes (midlatitudes) (Fig. 4b). This characterization is consistent with the spatial patterns of the SST and surface wind stress anomalies shown in Fig. 2. The temporal evolution of the SST tendency is largely determined by the heat flux anomaly at the ocean surface, including latent heat flux, sensible heat flux, and net shortwave radiation at the surface (Figs. 4d–f). Among the various components of the total heat flux anomaly (Fig. 3), latent heat flux anomaly resulting from the anomalous surface wind speed is dominant (Figs. 4c,d), particularly for the cooling in midlatitudes and warming in low latitudes, followed by the sensible heat flux anomaly (Fig. 4e), which is comparable with the latent heat flux anomaly in high latitudes. Overall, a positive (negative) anomaly of surface wind speed is tied in with negative (positive) heat flux and SSTA tendency, consistent with the WES mechanism.

The net longwave radiation at the surface with amplitude smaller than 5 W m^{-2} (not shown) is largely due to the change of SST. From boreal fall to winter the net shortwave radiation anomaly at the surface was up to 10–15 W m^{-2} to the south of 30°N and, together with the latent heat flux, enhanced the local SSTA (Fig. 4f). The enhanced shortwave radiation implies a positive feedback between the SSTA and low-stratus cloud over the eastern subtropical and tropical ocean, due to the fact that occurrence of low clouds favors cold SST in the regions. When the SST becomes warm (cold), low cloud amounts decrease (increase), resulting in more (less) shortwave radiation reaching the sea surface and further warming (cooling) the ocean (Tanimoto and Xie 2002; Huang and Hu 2007).

These results about the thermodynamical processes involved in the air–sea interaction in the North Atlantic are generally consistent with the conclusions from our previous works examining the physical processes associated with the leading modes of variability in the Atlantic Ocean (Hu and Huang 2007a, 2006a,b). Overall, it is suggested that surface heat flux associated with atmospheric circulation anomalies plays a dominated role in the interannual variability of SSTA in the North Atlantic. However, SST feedback to the atmosphere may also have some contribution to the persistence of the atmospheric and oceanic anomalies in the North Atlantic during 2009–10, which is discussed next.

b. Contribution of Atlantic SST feedback

Although it has been well documented that the atmospheric response in the NH to SSTA is largely due to the tropical Pacific SSTA (Fig. 3 of Hoerling et al. 1997; Fig. 11 of Hoerling and Kumar 2002; Kumar et al. 2005), the Atlantic SST feedback may also contribute to the persistent negative phase of the NAO. Previous works have suggested that Atlantic SST feedbacks on the atmospheric circulation play a role in sustaining coherent ocean–atmosphere anomalies on seasonal and longer time scales (Xie and Philander 1994; Chang et al. 1997; Hurrell et al. 2003; Czaja et al. 2003; Liu and Wu 2004; Ciasto et al. 2011). For instance, Huang and Shukla (2005) suggested that a positive feedback between the ocean and atmosphere may be responsible for the persistence of the horseshoe pattern in the subtropics during summer.

To examine the Atlantic SST feedback on the NAO, the contribution of Atlantic SST forcing on the atmosphere in the North Atlantic is estimated using AGCM simulations forced by observed SST in the Atlantic Ocean from 30°S northward and climatological SST elsewhere. The general patterns of observed H_{500} anomalies in the North Atlantic are reproduced to some extent in some months (Fig. 5). Particularly, it is noted that the local SST feedback had a positive contribution to the NAO throughout almost the whole period (Figs. 5 and 6). For example, the meridional gradient of the H_{500} anomaly—defined as the differences of the regional mean between 30°–50°N, 100°W–20°E and 50°–70°N, 100°W–20°E and used to measure the NAO (Czaja and Frankignoul 2002; Hu and Huang 2006c)—are qualitatively reproduced in April 2009, June 2009–May 2010, and August 2010 (Fig. 6). The correlation between the two time series in Fig. 6 is 0.49, suggesting that the Atlantic SST feedback did contribute to the persistent negative phase of the NAO during 2009–10. This is consistent with Czaja and Frankignoul (2002) and Zhang et al. (2010), who suggest that part of the NAO monthly anomaly is associated with the preceding SSTA in the North Atlantic and may be predictable.

In the tropics from JJA 2009 to JJA 2010 the Atlantic SST-forced experiment (Figs. 7c–f) shows a consistent weakening of the northeast trades, suggesting that the observed weakening of tropical winds during this period (Figs. 2d–f) is partly forced by the Atlantic SSTA. Since the weakened surface winds also keep the SST warm through the WES feedback, the sensitivity experiment here also demonstrates that changed SST, in return, can alter the surface winds, suggesting that air–sea coupling is involved in the persistent atmospheric and oceanic anomalies in the tropical Atlantic during 2009–10. However, in the extratropics, the AGCM sensitivity experiment results bear little resemblance to the observations (Figs. 2 and 7). That may be due to the fact that there is large internal noise, and dynamical, instead of thermodynamical processes, may play a more important role in the extratropics than in the tropics. This is also consistent with the previous finding that the AGCM experiment usually gives a weak response in the extratropics (Liu and Wu 2004), and the observed anomaly can be dominated by a "noise" component unrelated to the SSTA. This may be a factor causing the discrepancies between the observations and simulations in addition to the potential model biases.

We also note a relatively stronger influence of SSTA in cold seasons (Fig. 6b), consistent with the strong seasonality of the air–sea interaction in the North Atlantic Ocean. The overall amplitudes of the simulated anomalies in the cold season are about 20%–30% of the observed ones, and observed anomalies in the other months are not well simulated (Fig. 6). This evidence suggests that the SST forcing on the atmospheric circulation does have a contribution, but it may be small to the long-term persistent negative phase of the NAO.

Putting the anomalies in the North Atlantic during June 2009–August 2010 into the context of global

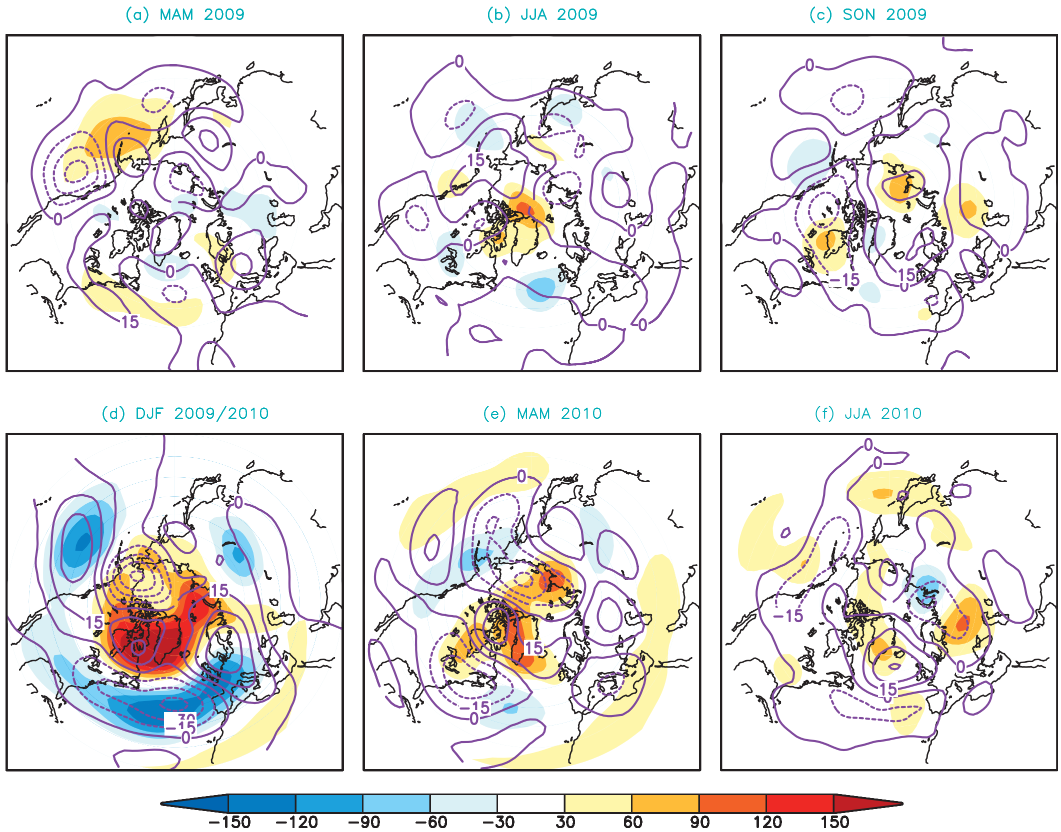

FIG. 5. Seasonal-mean geopotential height anomalies at 500 hPa during MAM 2009–JJA 2010 of R2 (shading) and GFS simulations forced by observed SST in the Atlantic Ocean alone (contour; interval 15 m).

variations, it is suggested that the anomalies in the North Atlantic were generated as a juxtaposition of both NAO-induced heat flux anomalies and influence of the ENSO event in 2009–10. The SST feedback may enhance the persistency and intensity of the atmospheric and oceanic anomalies. As discussed in the next section from a historical perspective, the in-phase combination of the impact from the negative phase of the NAO and the maturing phase of the strong El Niño event in 2009–10 was the primary reason for the record-breaking positive SSTA in the MDR since 1950 (Fig. 1). Moreover, to some extent the long-term trend may also affect the persistent anomalies in the North Atlantic during 2009–10.

4. Historical perspective and long-term trends

In the previous section, we demonstrated that the atmospheric and oceanic anomalies in the North Atlantic during 2009–10 were closely associated with a strong El Niño event and persistent negative phase of the NAO as well as SST feedback. Here, to put the analysis for this specific period in a historical context, we examine the statistical connection of SSTA in the North Atlantic with the ENSO and NAO, as well as the impact of the long-term trend.

a. Statistical relation of ENSO and NAO with the North Atlantic SST

Figure 8 shows the lead and lag correlations of the zonally averaged monthly mean SSTA in the North Atlantic with the *inverted* monthly mean NAO index (Fig. 8a) and Niño-3.4 index (Fig. 8b), as well as the lead and lag correlations between the Niño-3.4 and NAO indices (Fig. 8c) during 1950–2009. The SST correlations with the *inverted* NAO index (Fig. 8a) show a tripole pattern—positive (negative) in low and high latitudes (midlatitudes) when the index is negative—which is consistent with the SSTA pattern shown in Fig. 2 and the SSTA tendency pattern shown Fig. 4b. The maximum correlation occurs when the NAO leads SSTA by 1 month, suggesting that the SSTAs are mainly forced by the NAO. On the other hand, the amplitude of the correlation is small, which might be due to the fact that the zonal average SSTA was used in the correlation calculation. Since the NAO-associated SST anomalies are

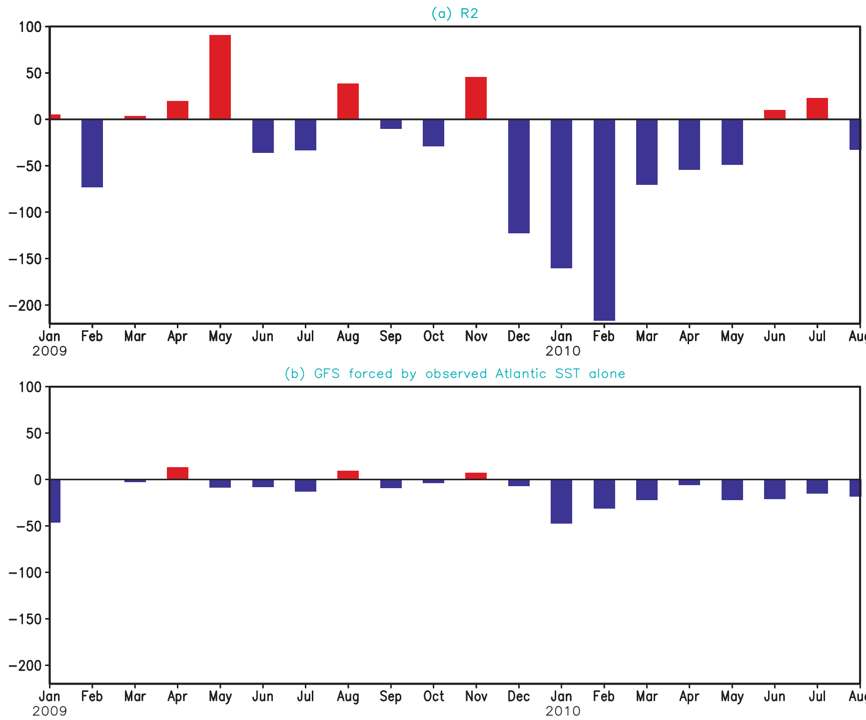

FIG. 6. Monthly mean anomalies of the meridional gradient of H_{500} (m) between its regional means in 30°–50°N, 100°W–20°E and 50°–70°N, 100°W–20°E for the (a) R2 and (b) GFS simulation forced by observed SST in the Atlantic Ocean alone. The linear correlation between the two time series is 0.49.

largely a horseshoe or tripole-like pattern with appreciable zonal heterogeneity, the zonal average makes the signal weak. The small correlation may also be caused by the strong internal variability and the large seasonality of the NAO, particularly its strong seasonal migration in the meridional direction (Portis et al. 2001; Hurrell and Deser 2009). The major impact of the NAO on the North Atlantic SST is during boreal winter and early spring, and the lack of NAO coherence and persistence in boreal summer may also lead to a weak SST imprint. In addition, interdecadal change of the NAO-associated spatial pattern (Hilmer and Jung 2000) may also be a factor weakening the long-term statistical correlation between the NAO and North Atlantic SST.

Besides the NAO, ENSO is another factor affecting tropical Atlantic SST variability (Czaja et al. 2002, 2003; Liu et al. 2004; references therein). Figure 8b displays the lead and lag correlation between the Niño-3.4 index and the zonal averaged SSTA. Maximum positive correlations are seen between the equator and 30°N when the index leads the SSTA by 3–8 months, and the maximum negative correlations are present along the equator when the index lags the SSTA by 6–12 months. The amplitude of the positive correlation coefficient reaches 0.4, which is larger than the corresponding correlation with the NAO shown in Fig. 8a, suggesting a more robust and longer persistent connection between the ENSO and SSTA in the tropical and subtropical North Atlantic than between the NAO and SSTA. It should be indicated that the ENSO teleconnection is also seasonally dependent, with the tropical North Atlantic SSTA in boreal spring strongly correlated with the Niño-3.4 index at the previous winter.

These results about the connection of the SSTA in the tropical and subtropical North Atlantic with ENSO are generally consistent with previous works (e.g., Curtis and Hastenrath 1995; Enfield and Mayer 1997; Xie and Carton 2004; Wang 2002; Liu et al. 2004), and have been confirmed by regional coupling experiments of Huang et al. (2002) and Huang (2004), and model sensitivity experiments of Chang et al. (2006). Nevertheless, the impact of an El Niño event on the tropical North Atlantic in the following spring and early summer may depend on the end time of the El Niño event. For example, an El Niño event causes warming in the tropical North Atlantic in the following spring and early summer only if it does not end before April (Lee et al. 2008). For the El Niño event in 2009–10, the evidence of a persistent strong positive SSTA in the tropical central Pacific until April 2010, and a significant warming in the tropical

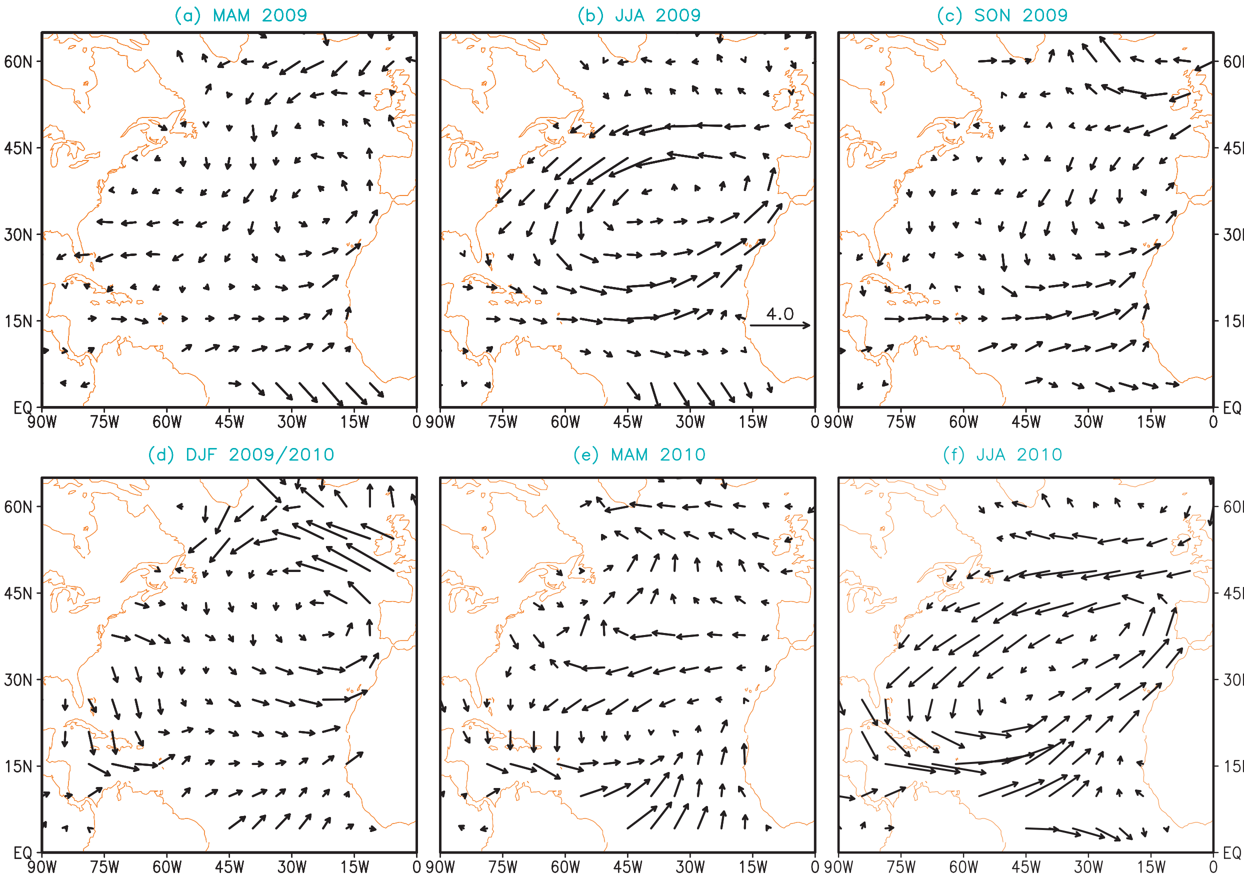

FIG. 7. Seasonal-mean surface wind anomalies at 10 m over the ocean during MAM 2009–JJA 2010 of the GFS simulations forced by observed SST in the Atlantic Ocean alone.

North Atlantic observed in the spring and summer, support the conclusion of Lee et al. (2008).

The above statistical relation and the simultaneous occurrence of the NAO and ENSO during spring 2009–summer 2010 suggest that both the El Niño event and negative NAO contributed to the record-breaking positive SSTA in the MDR in spring and summer 2010. This is generally consistent with Czaja et al. (2002). They found that, on the basis of a spring index of the tropical North Atlantic SST (5°–25°N), almost all SST extreme events in the region from 1950 to 1999 can be related to either ENSO or NAO. Since the SST events lag NAO and ENSO events, they further suggested that interannual variability in the tropical North Atlantic is interpreted as being largely a response to the NAO or remote ENSO forcing.

We also note that the NAO and ENSO are weakly correlated (Fig. 8c). The preceding El Niño (La Niña) slightly favors a negative (positive) phase of the NAO. Thus, the persistent negative phase of the NAO during summer 2009–summer 2010 may also be partially caused by the El Niño event. The ENSO and NAO are probably connected indirectly through the impact of ENSO on tropical North Atlantic SST, shown in Fig. 8b, which feeds back to the NAO (Hurrell et al. 2003). Also, there is a possibility that some additional forcings may have impact on both NAO and ENSO and add to the variability of both.

b. *Potential application in prediction*

The statistical lead and lag correlations shown in Figs. 8a,b provide a basis for predicting tropical North Atlantic SST using the NAO and ENSO indices as predictors (Hurrell 1996). Similar to the above statistical correlation, lead and lag regression equations between monthly mean SSTA in the North Atlantic and the Niño-3.4/NAO indices are built in each grid point in the North Atlantic. Then, using the regression equations, SSTA during March 2009–August 2010 are hindcast. In the prediction scheme, the Niño-3.4 index of the preceding fifth month and the NAO index of the preceding first month are used as predictors. Comparing the predicted seasonal mean in Fig. 9 with the observed anomalies in Fig. 2, it is shown that the general pattern of

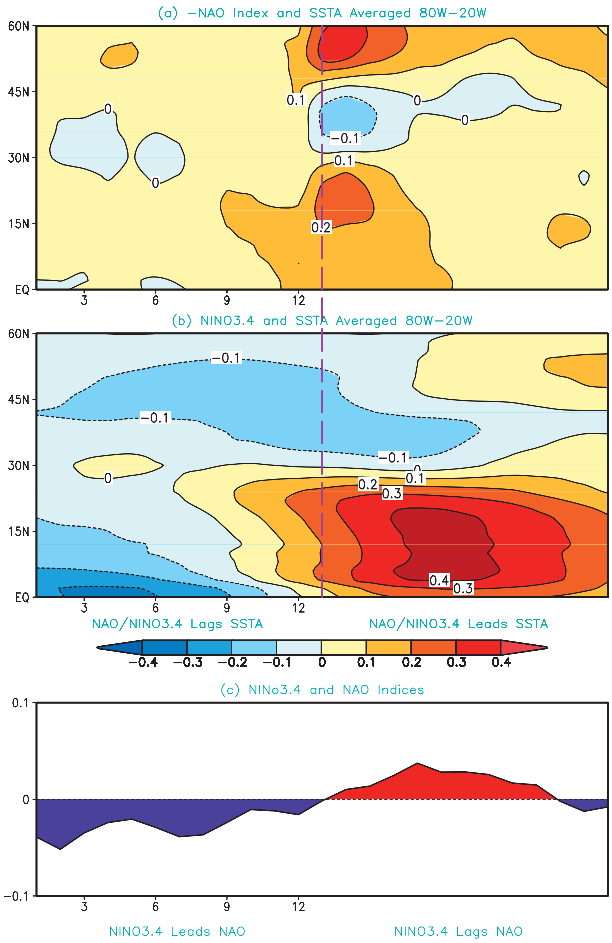

FIG. 8. Lead and lag correlation of monthly zonal mean SSTA averaged in 80°–20°W with the (a) inverted NAO index and (b) Niño-3.4 index, and (c) between the Niño-3.4 and NAO indices during January 1950–December 2009. Positive (negative) numbers on the *x* axis of (a) and (b) are the months of the indices leading (lagging) the SSTA, with a contour interval of 0.1. The linear trends of SSTA and NAO index were removed prior to the correlation calculations.

seasonal mean SSTA in the North Atlantic is well predicted, particularly for the seasons from DJF 2009/10 to JJA 2010. During these three seasons, the success of the prediction in mid- to high latitudes seems mainly due to the prediction based on the NAO index, but in the tropics it is mainly from the contribution of the prediction based on the Niño-3.4 index.

The pattern correlation between observed (Fig. 2) and hindcast (Fig. 9) seasonal mean SSTA in the region (0°–65°N, 80°W–20°E) shows that the hindcast using the Niño-3.4 index as predictor is better in capturing the SSTA pattern from MAM 2009 to MAM 2010 than that using the NAO index as predictor (Table 1). In JJA 2010, owing to the weakening influence of the El Niño event in 2009–10 on the North Atlantic, the correlation is lower using the Niño-3.4 index than using the NAO index as the predictor. The highest correlation is achieved in MAM 2010: 0.62 using the NAO index alone, 0.73 using the Niño-3.4 index alone, and 0.82 using both indices. The correlation is higher using both indices as predictors than using either one alone in all seasons, except for JJA 2009 due to the negative correlation contributed by the NAO index in that season. We also note that the correlations are −0.22 and 0.0 in JJA 2009 and SON 2009, respectively, when using the NAO index alone, suggesting that the SSTA may not be significantly affected by the NAO during these two seasons—it may due to the seasonality effect.

This result indicates the potential of using the NAO and ENSO indices as predictors to statistically forecast the SSTA pattern in the North Atlantic. However, we note that, although the general pattern of the SSTA is successfully reproduced based on the preceding Niño-3.4 and NAO indices, the amplitude of the SSTA is largely underestimated. For instance, in the tropical North Atlantic in MAM 2010, the maximum SSTA is between 1.2° and 1.5°C in observations (Fig. 2e), while it is between 0.4° and 0.5°C in the prediction (Fig. 9e). It seems that the underestimation of the amplitude of the SSAT in the prediction may be largely due to the weak correlations between the NAO and the SSTA (see Fig. 8a). Also, not including the long-term trends in the prediction may partly cause an underestimate of the positive SSTA in low and high latitudes. Furthermore, the forecast skill might be improved if the correlation is stratified with season.

To further examine if this qualitatively statistical relationship between ENSO–NAO and SST in the MDR holds for other years with extreme warm SST in the tropical North Atlantic, we analyze a few other strong positive SSTA events in the MDR in JJA. From Fig. 1b, we can see that, besides 2010, the largest positive SSTA in the MDR in JJA occurred in 1958, 1998, and 2005. The SSTA averaged in the MDR in JJA was 0.41°C in 1958, 0.53°C in 1998, and 0.79°C in 2005. Moreover, the pattern of SSTA in JJA of these years (Figs. 10b,e,h) was also analogous to that in JJA 2010 (Fig. 2f). Both ENSO and NAO conditions for these years fit the causal relationship that we elaborated for the 2009–10 case. For example, all three years were in the decay phase of El Niño events and were dominated by the negative phase of the NAO (Figs. 10a,d,g). Specifically, the negative phase of the NAO dominated since May 1957 for the 1957–58 case, since April 1997 for the 1997–98 case, and since February 2005 for the 2004–05 case. The similar combination of the ENSO and NAO phases in these years is associated with a similar SSTA pattern in the North Atlantic: warming in the tropics and high latitudes and cooling in middle latitudes.

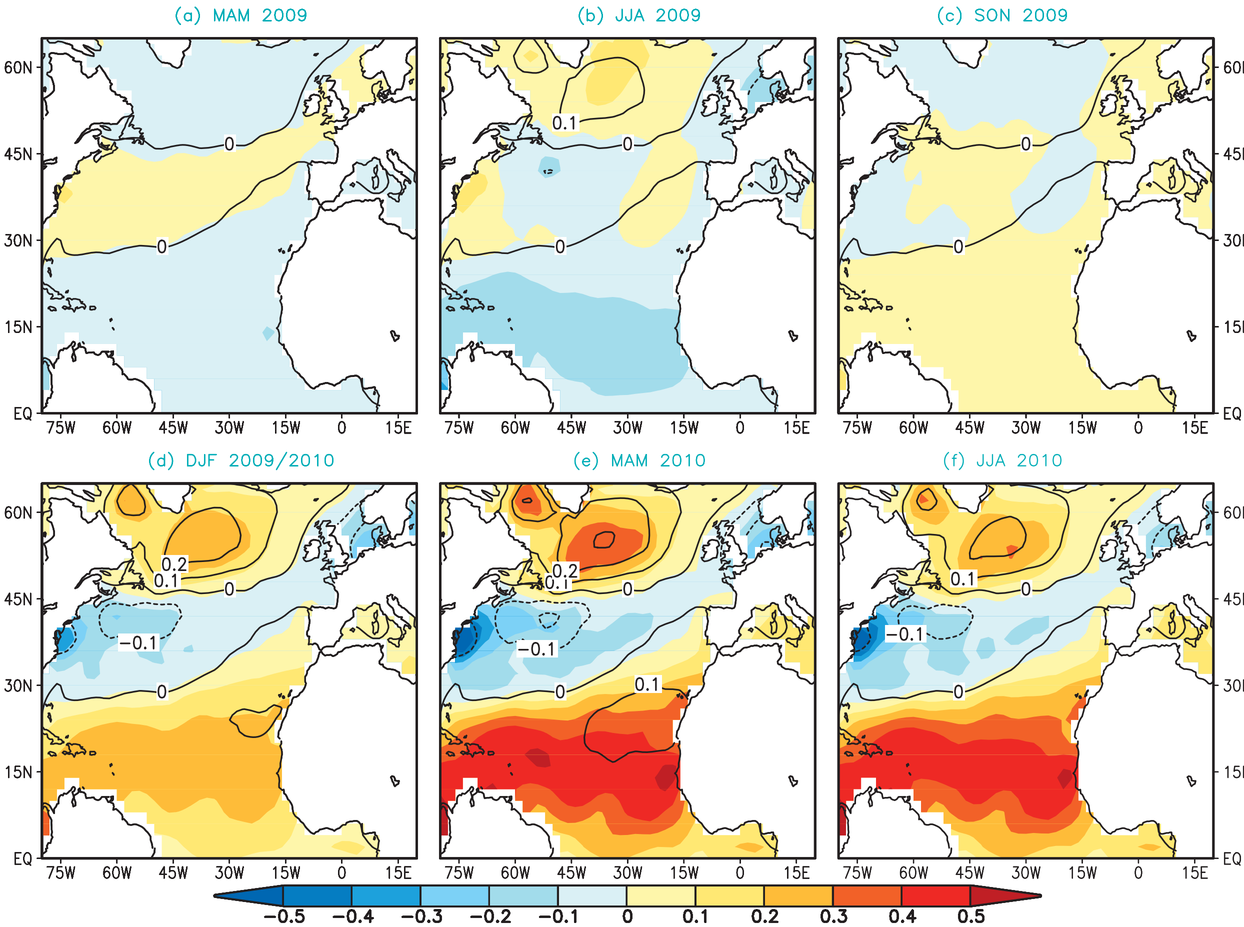

FIG. 9. Hindcasts of the seasonal mean SSTA (°C; contour interval 0.1) during MAM 2009–JJA 2010 using both Niño-3.4 and NAO indices as predictors (shading) and only using NAO index as a predictor (contour). The Niño-3.4 (NAO) index is 5-month (1-month) lead.

The general circulation anomalies during these three years also bear some similarities in the regions from the North Pacific to the North Atlantic (Figs. 10c,f,i). The circulation anomaly is a quasi-barotropic structure as seen in the geopotential height at 1000 hPa (H_{1000}) and H_{500} in winter. The PNA-like pattern is clear in DJF 1957/58 (Fig. 10c) and DJF 1997/98 (Fig. 10f), which may be due to the fact that it was in the decay phase of *strong* El Niños (Figs. 10a,d). In contrast, the anomalies in the North Pacific are much weaker in DJF 2004/05 (Fig. 10i), consistent with the decay phase of a *weak* El Niño (Fig. 10g). However, the overall circulation anomaly pattern in the North Atlantic sector is similar in these three years with positive (negative) anomalies in the northern (southern) part of the North Atlantic Ocean, consistent with the negative phase of the NAO.

These persistent atmospheric and oceanic anomalies set up an environment conducive to hurricane activity in the tropical North Atlantic. All four years (1958, 1998, 2005, and 2010) had above-normal Atlantic hurricane seasons, with 2005 having the most hurricane activity in the recent record. The Atlantic Accumulated Cyclone Energy (ACE) index in the North Atlantic (available online at http://en.wikipedia.org/wiki/Accumulated_cyclone_energy) is 121 in 1958, 182 in 1998, 248 in 2005, and 165 in 2010. For 1950–2009, the mean of ACE index is 101 and the median is 88.0.

TABLE 1. Pattern correlation between the hindcast (see Fig. 9) and observed (Fig. 2) seasonal mean SSTA in the region 0°–65°N, 80°W–20°E.

	Predictor		
Season	Niño-3.4 index	NAO index	Both Niño-3.4 and NAO indices
MAM 2009	0.61	0.36	0.62
JJA 2009	0.16	−0.22	0.05
SON 2009	0.24	0.0	0.25
DJF 2009/10	0.63	0.61	0.76
MAM 2010	0.73	0.62	0.82
JJA 2010	0.34	0.42	0.42

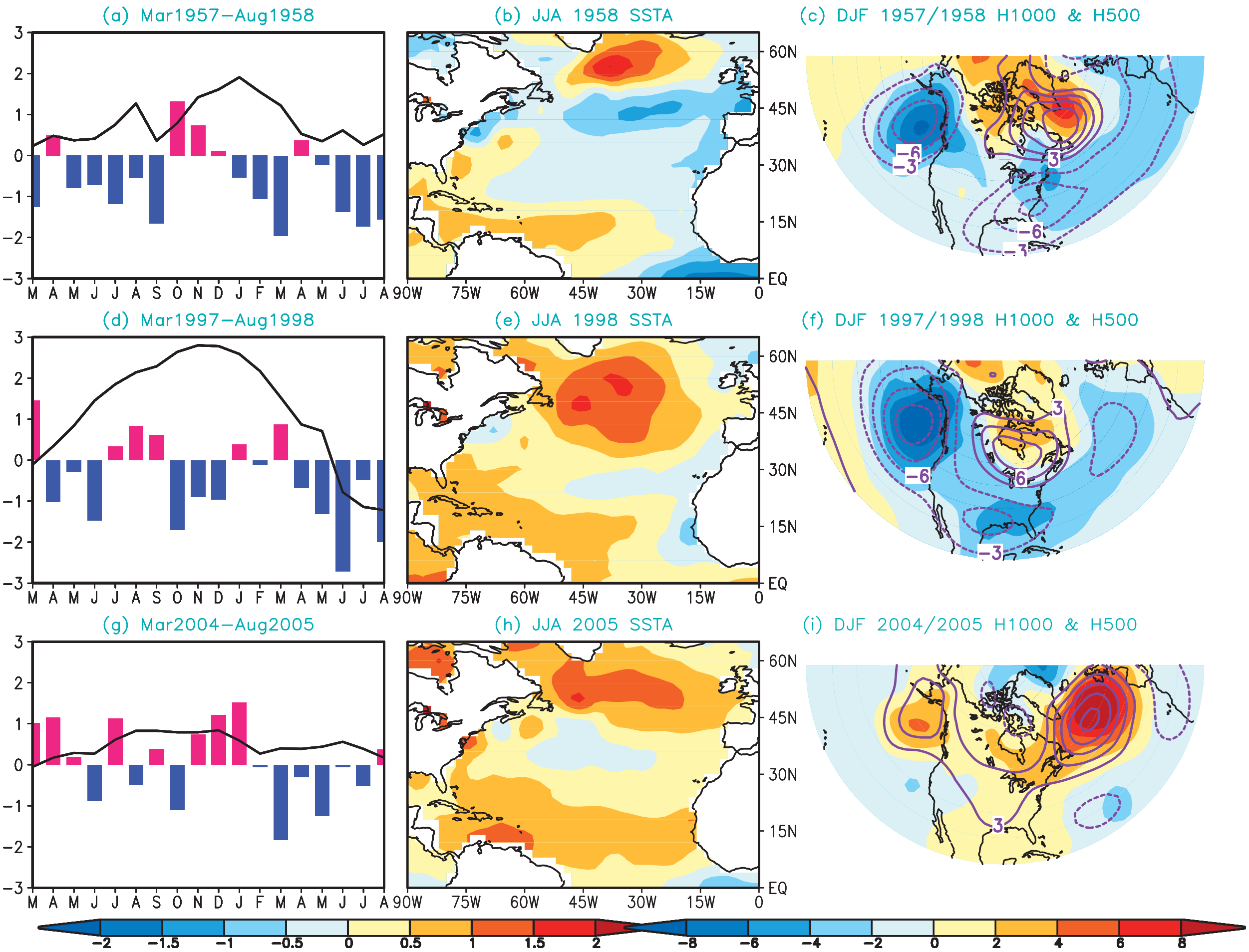

FIG. 10. (left) Monthly mean NAO (bars) and Niño-3.4 (line) indices during (a) March 1957–August 1958, (d) March 1997–August 1998, and (g) March 2004–August 2005. (center) SSTA in JJA of (b) 1958, (e) 1998, and (h) 2005. (right) Geopotential height anomaly at 1000 (shading) and 500 hPa (contour) in DJF of (c) 1957/58, (f) 1997/98, and (i) 2004/05. Contour interval is 3 m, and the zero line is suppressed.

c. *Impact of long-term trends*

We next discuss the June 2009–August 2010 variability in the context of long-term trends. Figures 11a and 11b display the anomalies averaged in June 2009–August 2010 and the linear trend during January 1979–December 2009. From a global perspective, there is almost no similarity between the averaged anomalies for this particular period and the linear trend. In the former (Fig. 11a), positive SSTAs were located in the tropical Pacific (apparently associated with the ENSO event in 2009–10), the Indian Ocean, and the tropical North and South Atlantic Oceans, while negative anomalies were observed in the North Pacific, the Southern Ocean, and midlatitudes of the North Atlantic. In contrast, the latter has a different spatial distribution with a positive trend in the western Pacific, Indian Ocean, and North Atlantic, but a negative trend in the eastern Pacific and South Ocean (Fig. 11b).

The long-term trend, however, does contribute to the magnitude of the observed persistence and the magnitude of SST anomalies in the North Atlantic during June 2009–August 2010. For example, when the linear trend during January 1979–December 2009 is removed, the negative SSTA in midlatitudes is intensified and the positive SSTA in high and low latitudes weakened (Fig. 11c). This suggests that the overall long-term warming trend in the North Atlantic enhanced the positive anomaly in the low and high latitudes and weakened the negative anomalies in midlatitudes during June 2009–August 2010. Quantitatively, the averaged SSTA is between −0.3° and −0.6°C for the negative SSTA in midlatitudes and is between 0.6° and 0.9°C for the positive SSTA in low latitudes (Fig. 11a). The corresponding values would be between −0.6° and −0.9°C, and between 0.3° and 0.6°C if the linear trends are removed. Thus, the long-term trends may account for about one-third of the warming in the

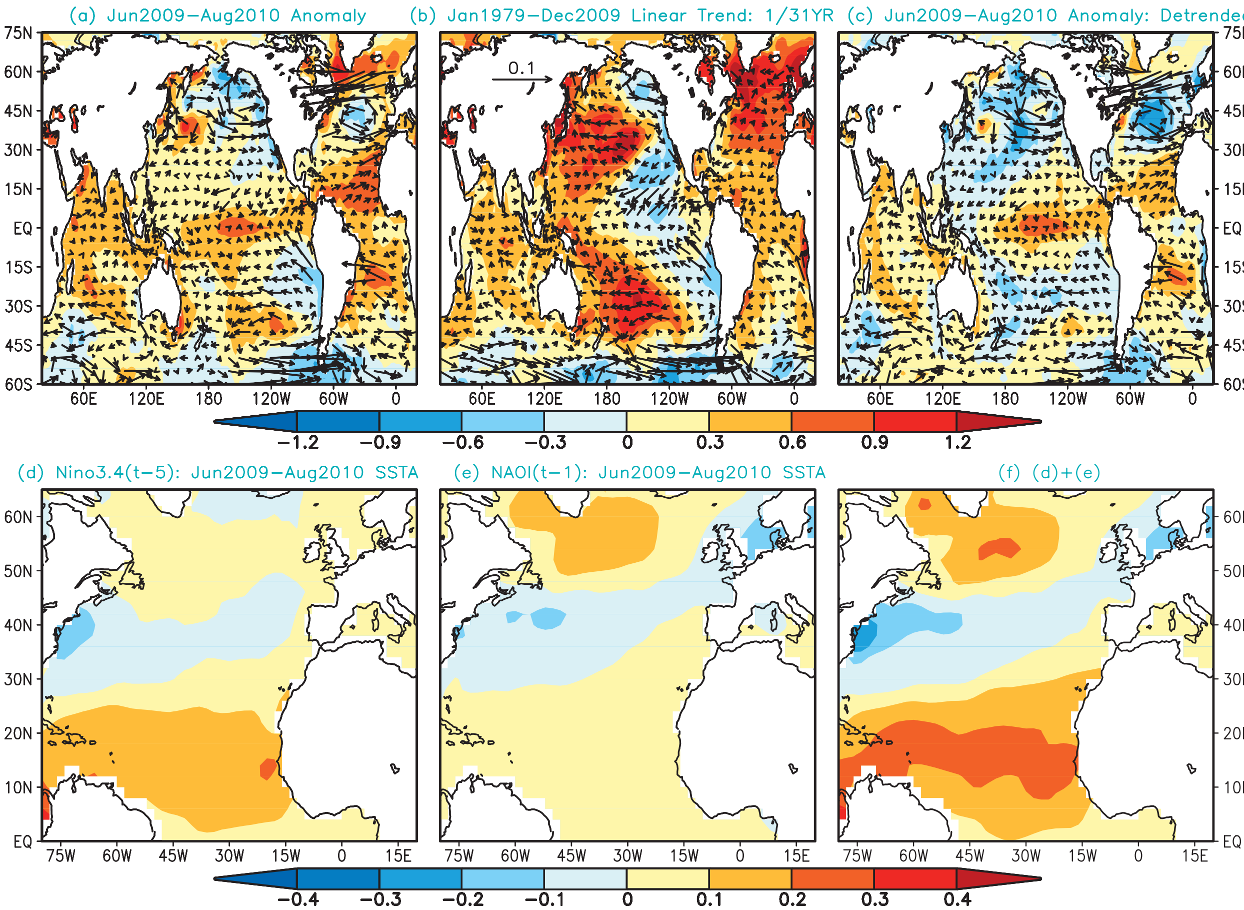

FIG. 11. SST (shading) and surface wind stress (vector): (a) anomalies averaged during June 2009–August 2010, (b) linear trend during January 1979–December 2009, and (c) anomalies averaged during June 2009–August 2010 with the linear trend removed. Hindcasts of mean SSTA averaged in June 2009–August 2010 (d) using the Niño-3.4 index with a 5-month lead and (e) using the NAO index with a 1-month lead; (f) the sum of (d) + (e). The units of the shading are degrees Celsius in (a) and (c) and degrees Celsius per 31 years in (b).

tropical Atlantic and weakened cooling in midlatitudes of the North Atlantic by about one-third. Nevertheless, we recognize that the nonlinear trend, for which the CO_2 time series may serve as a good proxy, may be a better choice to estimate the trend in the North Atlantic (Polyakov et al. 2010), and may modify the quantitative estimates from the linear trend analysis reported here.

To summarize, it is interesting to see that the overall pattern of SSTA in the North Atlantic Ocean averaged over June 2009–August 2010 can be reproduced using the Niño-3.4 index with a 5-month lead (Fig. 11d) and/or using NAO index with a 1-month lead (Fig. 11e). Consistent with the seasonal mean results, shown in Fig. 9, the warm event of ENSO had a greater contribution in low latitudes and the negative phase of the NAO had a greater contribution in high latitudes. However, the amplitudes of the hindcast for both negative and positive SSTAs from the individual factors (Figs. 11d,e) are much smaller than that of the observed SSTAs (Figs. 11a,c). The amplitudes of the hindcast SSTAs from the combination of both factors (Fig. 11f) are about one-third to one-half of the observed detrended SSTA, further suggesting the importance of the long trend and the amplification of the dynamical and thermodynamical processes to the persistent anomalies during June 2009–August 2010.

5. Discussion and conclusions

In this work, we analyze the air–sea interaction processes associated with the persistent atmospheric and oceanic anomalies in the North Atlantic and the record-breaking positive SSTA in MDR during summer 2009–summer 2010. In this analysis, we identify the contributions of the ENSO, NAO, as well as long-term trend to the anomalies from a historical perspective by using a variety of observational and analyzed or reanalyzed data and model sensitivity simulations. It is suggested that the record-breaking warming in the tropical North Atlantic during summer 2009–summer 2010 included a typical response to ENSO, which was *amplified* by the influence due to the negative phase of the NAO and long-term trend.

The persistent negative phase of the NAO was associated with active thermodynamic air–sea interaction. The surface wind stress anomaly associated with the NAO altered the ocean surface heat flux and changed the SSTA by a wind speed–evaporation–SST mechanism. The total heat flux was dominated by latent and sensible heat flux, while the shortwave radiation enhanced the SSTA to a certain degree. The thermodynamical processes played an important role in the SSTA in the tropical and subtropical North Atlantic Ocean. Actually, the long persistence of the atmospheric and oceanic anomalies in the North Atlantic may have been due to coupling of the ocean and atmosphere. Through conducting some AGCM sensitivity experiments forced by the observed SST in the Atlantic Ocean alone, it is demonstrated that the feedback of Atlantic SSTA on the NAO enhanced persistence of the negative phase of the NAO to some extent. Moreover, as compared with the observed long-term trends in the last 31 years, it is suggested that the anomalies during summer 2009–summer 2010 were mainly short-term fluctuations, particularly for the cooling in the midlatitudes of the North Atlantic. However, overall warming trends enhanced the warming in high and low latitudes and weakened the cooling in midlatitudes.

Combination of the impact from the El Niño event in 2009–10 and the negative phase of the NAO as well as the long-term trend resulted in the record-breaking positive SSTA in the MDR. By using the statistical relationship, the SSTA pattern in the North Atlantic can be reasonably well predicted by using the preceding ENSO and NAO as predictors. That may imply some additional predictability of Atlantic hurricane activity using these predictors.

It is clear that in order to predict the North Atlantic SST, we have to successfully predict ENSO and NAO. It has been well known that ENSO can be predicted reasonably well a few seasons in advance (Chen and Cane 2008; references therein). However, the assessment of predictability of the NAO is controversial. It has been documented that the low-frequency part of the NAO can be forced by SSTA (Rodwell et al. 1999; Latif et al. 2000). Later, Czaja and Frankignoul (2002) also found that SSTA in the North Atlantic in spring and summer may itself be a predictor for the following winter NAO. The anomalous evolution of air–sea interaction in the North Atlantic during summer 2009–summer 2010 was indeed consistent with the so-called NAO interseasonal prediction signals documented in previous investigations, such as Czaja and Frankignoul (2002), Cassou et al. (2004), and Saunders and Qian (2002). Czaja and Frankignoul suggested that 15% of the NAO monthly anomaly variance in winter may be predictable by using the preceding spring and summer SSTA in the North Atlantic. However, the 15% predictability might be the average predictability with a larger contribution from a few anomalous NAO years (Hu and Huang 2006c). By using two NAO indices in winter, Hu and Huang (2006c) compared their connection with the preceding SSTA in the North Atlantic. They found that, although the two indices are highly correlated, one index is significantly correlated with a tripole pattern of SSTA in the North Atlantic up to the preceding spring, and may have some predictability up to 7–9 months in advance, and the other one has little predictability beyond the SSTA two months prior to early winter. To gain further insights into the seasonal–interannual predictability over the North Atlantic, continued examination of the air–sea interaction effects presents an interesting challenge.

Moreover, the NAO/AO is also associated with stratospheric processes, particularly in the NH winter, and the variability in the lower-stratospheric polar vortex may provide some prediction potential for the NAO/AO (Thompson et al. 2003; Cohen et al. 2010; references therein). Furthermore, the NAO displayed a long-term change, which may be associated with the meridional heat transport of the fluctuating overturning circulation and sea ice extension (Hilmer and Jung 2000), as well as increasing greenhouse gas concentrations (Ulbrich and Christoph 1999; Gillett et al. 2003; Hu and Wu 2004).

In the North Atlantic, besides surface fluxes, a slowly evolving subsurface oceanic temperature anomaly (OTA) might also play a role in affecting the SSTA, especially in midlatitudes. An analysis of OTA also indicates the extent of penetration of the influence of surface variability, which may govern the time scale and memory associated with the extreme atmospheric circulation anomalies that occurred during summer 2009–summer 2010. In fact, the distribution pattern of the SSTA (Fig. 2) is quite consistent with OTA at both 50 and 300 m north of 30°N (not shown), although the similarity is confined well above 300 m in low latitudes. This shallower (deeper) penetration of OTA in the low (high) latitudes may partially reflect the latitude dependence of the ocean mixed layer depth. The relatively shallow OTA in low latitudes implies the dominance of air–sea interaction through heat flux in generating the OTA within a shallow ocean layer. Vertical coherence of the OTA in the mid- and high latitudes may suggest a connection with the anomalous upper-ocean heat content probably associated with perturbation of the Gulf Stream extension and deep-water convection, which deserves further investigation.

The results of OTA are consistent with that of the tendency due to dynamical processes, for example, advection, Ekman transport, and heat flux (not shown) inferred based on an analysis of the mixed layer heat budget diagnosed using outputs from GODAS (Huang et al. 2010). Both dynamical processes and heat flux have a large contribution to the SST tendency in mid- to high latitudes. In comparison with the heat flux, the dynamical processes have a relatively smaller contribution in the tropical and subtropical North Atlantic and act to damp the total tendency during DJF 2009/10–JJA 2010. This is generally consistent with Seager et al. (2000). In addition, the reemergence and spread of cold ocean temperature anomalies in the subsurface ocean in late fall and winter might also have helped to enhance the tripole SSTA pattern (Timlin et al. 2002).

Acknowledgments. We appreciate the comments of Michelle L'Heureux and Hui Wang, M. Alexander, and the anonymous reviewers, which significantly improved the manuscript. Thanks also are given to Boyin Huang, Mingyue Chen, and Scott Weaver for their help. Huang is supported by the NOAA CVP Program (NA07OAR4310310) as well as the COLA omnibus program from NSF (ATM-0830068), NOAA (NA09OAR4310058), and NASA (NNX09AN50G).

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