Atmospheric Teleconnections of Tropical Atlantic Variability: Interhemispheric, Tropical–Extratropical, and Cross-Basin Interactions

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ABSTRACT

In this paper, the atmospheric teleconnections of the tropical Atlantic SST variability are investigated in a series of coupled ocean–atmosphere modeling experiments. It is found that the tropical Atlantic climate not only displays an apparent interhemispheric link, but also significantly influences the North Atlantic Oscillation (NAO) and the El Niño–Southern Oscillation (ENSO). In spring, the tropical Atlantic SST exhibits an interhemispheric seesaw controlled by the wind–evaporation–SST (WES) feedback that subsequently decays through the mediation of the seasonal migration of the ITCZ. Over the North Atlantic, the tropical Atlantic SST can force a significant coupled NAO–dipole SST response in spring that changes to a coupled wave train–horseshoe SST response in the following summer and fall, and a recurrence of the NAO in the next winter. The seasonal changes of the atmospheric response as well as the recurrence of the next winter's NAO are driven predominantly by the tropical Atlantic SST itself, while the resulting extratropical SST can enhance the atmospheric response, but it is not a necessary bridge of the winter-to-winter NAO persistency. Over the Pacific, the model demonstrates that the north tropical Atlantic (NTA) SST can also organize an interhemispheric SST seesaw in spring in the eastern equatorial Pacific that subsequently evolves into an ENSO-like pattern in the tropical Pacific through mediation of the ITCZ and equatorial coupled ocean–atmosphere feedback.

1. Introduction

Sea surface temperature (SST) over the tropical Atlantic exhibits substantial interannual-to-decadal climate variability (e.g., Hastenrath 1984, 1990). Associated with changes of the SST are modulations in the strength of the southeast and northeast trades as well as the position and intensity of the intertropical convergence zone (ITCZ), that may profoundly impact the rainfall in the surrounding landmasses, primarily northeastern Brazil and sub-Saharan West Africa (see a review by Marshall et al. 2001).

Several mechanisms have been put forward to explain the origins of tropical Atlantic variability (TAV; see a review by Xie and Carton 2004). One challenge in understanding the TAV is that this region is subject to multiple competing forcing including both local and remote resources. While many studies have emphasized the effects of external forcing remotely from ENSO (e.g., Curtis and Hastenrath 1995; Enfield and Mayer 1997; Saravanan and Chang 2000; Sutton et al. 2000; Czaja et al. 2002; Huang et al. 2002) and the North Atlantic Oscillation (NAO; e.g., Nobre and Shukla 1996; Czaja et al. 2002; Xie and Tanimoto 1998; Wu and Liu 2002), studies also indicate a substantial portion of the TAV arising from coupled ocean–atmospheric interaction locally in the tropical Atlantic (e.g., Huang and Shukla 2005; Wu et al. 2004). Studies have suggested that the dominant feedback within the tropical

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Atlantic appears to be associated with the cross-equatorial SST gradient, wind-induced evaporation, and seasonal migration of the ITCZ. Chang et al. (1997) hypothesized that a positive thermodynamic wind–evaporation–SST feedback (WES; Xie and Philander 1994) can sustain the cross-equatorial SST gradient to give rise to an interhemispheric SST dipole. A positive cross-equatorial SST gradient sets up a negative meridional pressure gradient, which induces southerly cross-equatorial winds and anomalous southwestly (northeastly) trades to reduce (increase) evaporative cooling in the north (south) of the equator to further enhance the cross-equatorial SST gradient. Observations, however, suggest that this positive feedback only appears in the deep Tropics (e.g., Czaja et al. 2002; Chiang et al. 2002), and is also regulated by the seasonal migration of the ITCZ (Okajima et al. 2003). It still remains uncertain whether the unstable coupled ocean–atmospheric interaction can organize the tropical Atlantic air–sea anomalies into an interhemispheric seesaw via the coupled WES feedback. Some AGCM studies found the interhemispheric interaction in the tropical Atlantic basin are very weak (e.g., Dommenget and Latif 2000). Analyses from coupled models also give different feedback strengths between SST, wind, and surface heat flux (e.g., Frankignoul et al. 2004). Therefore, it still remains as a matter of debate about the nature of the interhemispheric interaction in the tropical Atlantic based on the statistical analyses of observations and fully coupled models as well as AGCM modeling studies.

The coupled ocean–atmospheric interaction in conjunction with the meridional migration of the ITCZ may affect the climate outside this region. Past studies tend to focus on the passive response of the tropical Atlantic climate to the NAO and ENSO (e.g., Czaja et al. 2001). It is conceivable that the diabatic heating associated with the ITCZ changes caused by the tropical interhemispheric SST change may modulate the subtropical jet (Nobre and Shukla 1996; Robertson et al. 2002; Cassou et al. 2004) through forced Rossby wave train dynamics. AGCM studies have attempted to assess the influence of the tropical Atlantic SST anomalies on the extratropical atmosphere, although these studies have produced diverse results (e.g., Watanabe and Kimoto 1999; Robertson et al. 2000; Okumura et al. 2001; Cassou and Terray 2001). Recent interests on the tropical influence on the extratropics is further elevated by some observational studies where a statistical link between the so-called summer North Atlantic SST horseshoe (NAH; an SST pattern with anomaly in the western subtropical North Atlantic surrounded by anomalies of opposite polarity extending from the eastern subtropics poleward to the eastern subpolar North Atlantic) and the earlier winter NAO is found (e.g., Czaja and Frankignoul 2002). AGCM studies by Cassou et al. (2005) suggest that the anomalous tropical convection associated with ITCZ displacement in summer can potentially force the SST horseshoe pattern in the North Atlantic, which can further influence the earlier winter NAO. While the modeling study of Cassou et al. (2005) tends to support the observed statistic link between the summer NAH and the earlier winter NAO, a more recent modeling study by Peng et al. (2005) suggests that this statistical link may be largely attributed to the persistent forcing of the seasonally varying atmosphere by tropical SST anomalies without any apparent link with the NAH. Nevertheless, these modeling studies consistently point to the influence of the tropical Atlantic SST anomalies on the extratropical coupled ocean–atmosphere interactions.

In addition to the potential influence on the Atlantic climate, recent coupled GCM studies have also demonstrated a significant response in the tropical Pacific concurring with the Atlantic interhemispheric SST seesaw resulted from a weakening of the Atlantic meridional overturning circulation (e.g., Dong and Sutton 2002; Zhang and Delworth 2005). Although these studies suggested a potential link from the Atlantic to the tropical Pacific, the mechanisms for such a teleconnection still remain not well understood. It is sometimes difficult from a fully coupled experiment to isolate the causality due to the complexities of coupled ocean–atmosphere feedbacks and teleconnections.

In this study, we explore the coupled ocean–atmosphere interaction in the tropical Atlantic and its impacts on the extratropical North Atlantic and the tropical Pacific by performing a series of coupled ocean–atmosphere GCM experiments. The major objectives of this paper are to assess 1) interhemispheric teleconnection within the tropical Atlantic, 2) seasonal impacts of the tropical Atlantic SST anomalies on the extratropical North Atlantic coupled ocean–atmosphere interaction, and 3) impacts of the tropical Atlantic variability on the tropical Pacific. The paper is organized as follows: section 2 describes the coupled model and the experimental strategy, section 3 presents the model results, and section 4 provides a summary and further discussions.

2. The model

The model we used is the Fast Ocean–Atmosphere Model (FOAM) version 1.5 (Jacob 1997). The atmospheric model is a parallel version of National Center for Atmospheric Research (NCAR) Community Cli-

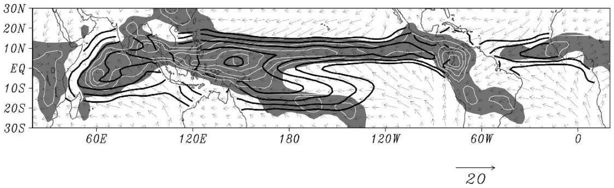

FIG. 1. Annual mean precipitation (white contours at 2 mm day^{-1} intervals; areas with precipitation exceeding 4 mm day^{-1} are shaded), SST (black contours at 1°C intervals; the minimum value for contours is 27°C), and surface wind (vectors, units are in m s^{-1}) in the FOAM model.

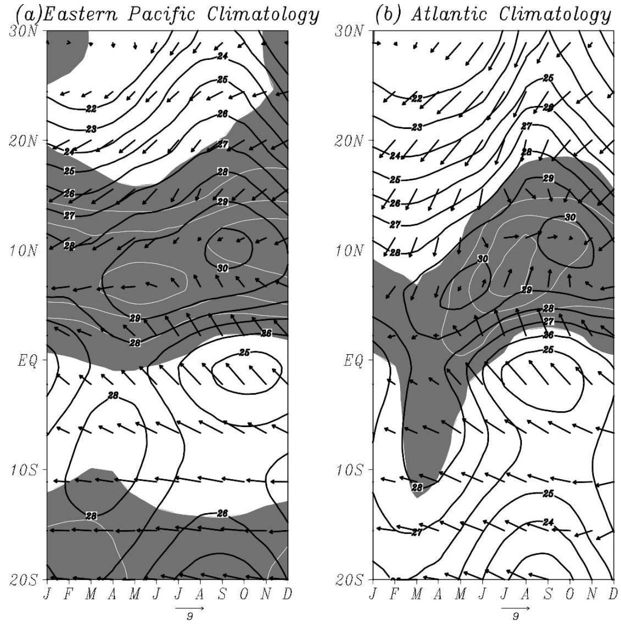

FIG. 2. Time–latitude section of FOAM climatological SST (black contours at 1°C intervals), surface wind (vectors, units are in m s^{-1}), and precipitation (white contours at 2 mm day^{-1}; shading >2 mm day^{-1}). (a) The eastern tropical Pacific (zonally averaged over 180°–120°W) and (b) the tropical Atlantic (zonally averaged over 30°–20°W).

mate Model (CCM) 2.0 at R15, but with atmospheric physics replaced by CCM3, and vertical resolution of 19 levels. The ocean model is similar to the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOM) with a resolution of 1.4° latitude × 2.8° longitude × 32 levels.

FOAM produces a tropical climatology similar to most of the state-of-the-art climate models (Liu et al. 2004). Although there are still some apparent deficiencies, the cold tongue and the double ITCZ bias as seen in most of coupled GCMs (Davey et al. 2002) have been reduced (Fig. 1), which is largely attributed to the incorporation of shortwave attenuation in the upper ocean. For instance, in the tropical Pacific, the warm pool and cold tongue appear correctly located in the west and east (Fig. 1), with a dominant ITCZ rainband close to 10°N in summer and near to the equator in winter (Fig. 2a). In the tropical Atlantic, the marine ITCZ reasonably stays north of the equator collocated with high SST, although the high SST in the west has a much smaller meridional dimension than the observed (Fig. 1). From January to April, the trade winds converge onto the equator from both hemispheres with a rainband close to the equator (Fig. 2b). From June to October, as the equatorial cold tongue develops, the ITCZ migrates north of the equator following the northward displacement of high SST (Fig. 2b). FOAM has a wetter climate in the western tropical Pacific than the observed. Over the western tropical Atlantic, the convection centers are somewhat displaced northwest of Amazon and too far south along the Peru coast (Fig. 1). FOAM also produces reasonable ENSO (Liu et al. 2000), tropical Atlantic variability (Wu and Liu 2002), and North Atlantic climate variability (Wu and Liu 2005).

3. Modeling results

a. Tropical Atlantic interhemispheric interaction

To investigate the potential interhemispheric interaction in the tropical Atlantic, we perform a set of coupled experiments in which a mixed layer temperature anomaly is initiated in the north tropical Atlantic (NTA). The imposed temperature anomaly has a bell-shaped distribution in both zonal and meridional directions and an amplitude of 2°C at 15°N, and extends uniformly to a depth of 200 m. The mixed layer temperature anomaly is initiated on the first day of January and is tracked for 2 yr. A total of 40-member ensemble experiments with each experiment starting from an equilibrium state of a long control fully coupled simulation are performed.

This initial value (IV) approach can allow us to track the evolution of SST and associated atmospheric response. This experiment is referred to as IV-NTA. The IV-NTA experiment is different from our earlier partial coupling (PC) modeling study, in which a fixed SST anomaly is prescribed for the atmosphere in the NTA (PC-NTA; Wu et al. 2005). In the PC-NTA, the SST forcing for the atmosphere is held constant with time over the NTA and the ocean model is still driven by the output of the atmospheric component. Therefore, in the PC region the atmospheric component is an (Atmospheric Model Intercomparison Program) AMIP-type setting. Such a setting may amplify the SST forcing and potentially distort the coupled ocean–atmosphere response. The IV approach here represents a more

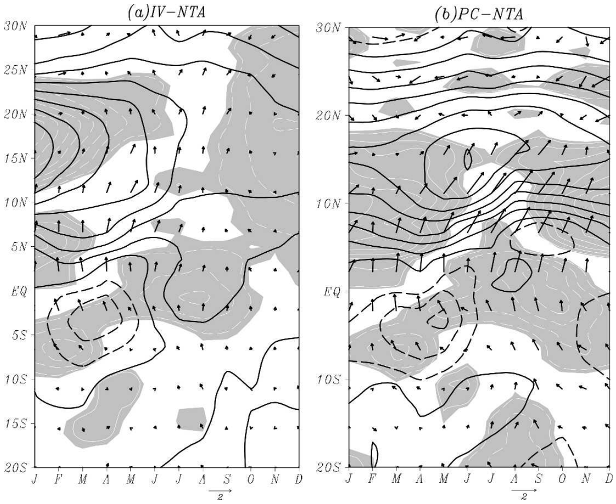

FIG. 3. Time–latitude section of SST (black contours at 0.2°C intervals), surface wind (vectors, units are in m s^{-1}) and surface heat flux (white contours at 3 W m^{-2}; shading >5 W m^{-2}) zonally averaged over 60°W–10°E. (a) The IV-NTA and (b) PC-NTA experiments.

natural approach for assessing the coupled ocean–atmosphere feedbacks (Liu and Wu 2004).

The model explicitly demonstrates that the coupled ocean–atmosphere interaction in the tropical Atlantic exhibits a strong seasonality, with an apparent interhemispheric link in spring (Fig. 3a). In spring, the warm NTA SST anomaly sets up an anomalous meridional pressure gradient that induces anomalous southerly cross-equatorial winds (Fig. 3a). In the northern deep Tropics, the anomalous southerly winds decelerate the northeast trade winds (Fig. 2b), reducing the evaporative heat loss, and thus generating warming in this area. The coupled WES response in the northern deep Tropics is consistent with previous modeling (e.g., Chang et al. 2000) and observational studies (e.g., Czaja et al. 2002; Chiang et al. 2002; Frankignoul et al. 2004). South of the equator, the anomalous southerly winds accelerate the southeast trade winds (Fig. 2b) that intensify the evaporative heat loss and result in cold SST anomalies from the equator to 10°S forming an interhemispheric seesaw in the tropical Atlantic (Fig. 3). This interhemispheric seesaw appears to be more robust in the spring season (Fig. 4a), and is sometimes referred to as the tropical Atlantic dipole, although the two poles are not perfectly antisymmetric about the equator.

The interhemispheric seesaw in the IV-NTA is largely similar to that in our earlier PC-NTA (Wu et al. 2005; Figs. 3b and 4b), although the magnitudes of SST are slightly stronger in the PC-NTA, suggesting the interhemispheric seesaw appears to be a robust feature in spring, at least in this model. In the IV-NTA, the warm anomaly in the NTA decays rapidly in winter and spring due to the atmospheric damping incurred by the air–sea temperature contrast, while in the PC-NTA the SST remains largely unchanged.

After spring, the cooling in the south eventually decays and is subsequently replaced by a warming, albeit weak, in summer (Figs. 3a and 4c). This warming is generated through the advection of the warm NTA SST by the mean equatorward oceanic current (not shown), while the atmosphere acts to damp the SST anomaly. In contrast, in the PC-NTA, while the cooling also decays after spring, it tends to intrude into the northern deep Tropics, with maximum cooling located in the west (Fig. 4c). This cooling is largely associated with the coupled interactions of the WES feedback and the mean ITCZ migration in summer due to an exaggerated SST in the NTA, which overwhelms the advection of the warm NTA SST by the mean equatorward ocean current. It can be seen that associated with the northward intrusion, the anomalous southerly winds also extend to the northern subtropics in the following summer and fall (Figs. 3b and 4d). The northward shift of the coupled ocean–atmosphere pattern appears to be mediated by the seasonal migration of the ITCZ. From spring to summer, the ITCZ migrates from its southernmost position to its northernmost position. In summer, the warm NTA SST (which is much weaker in the IV-NTA) induces the anomalous southerly winds, that accelerate the southeast trades in the northern deep Tropics to enhance the evaporative heat loss, leading to a development of cold SST anomalies in this area. The cooling further intensifies the meridional pressure gradient, decelerates the northeast trades in the northern subtropics, leading to an intensification of the warming in that area (Fig. 3b). The warming in the NTA peaks in summer, lagging the peak of the cooling south of the equator by about a season. This phase lag reflects a further feedback of the STA cooling to the NTA SST through the coupled WES feedback in conjunction with the seasonal migration of the ITCZ. Nevertheless, although the PC experiment exaggerates the summer SST anomaly in the NTA, it demonstrates a coupled interaction of the WES feedback and the mean ITCZ in modulating the tropical Atlantic climate variability.

To further assess whether a seasonal interhemispheric link from the south tropical Atlantic (STA) to the NTA exists, another set of PC experiments is performed, in which a warm SST anomaly is imposed in the STA region (5°–25°S). In boreal winter and spring, the warm STA SST sets up a southward pressure gradient, inducing northerly cross-equator winds, which decelerate the southeast trades but accelerate the northeast trades, leading to warming in the southern deep Tropics

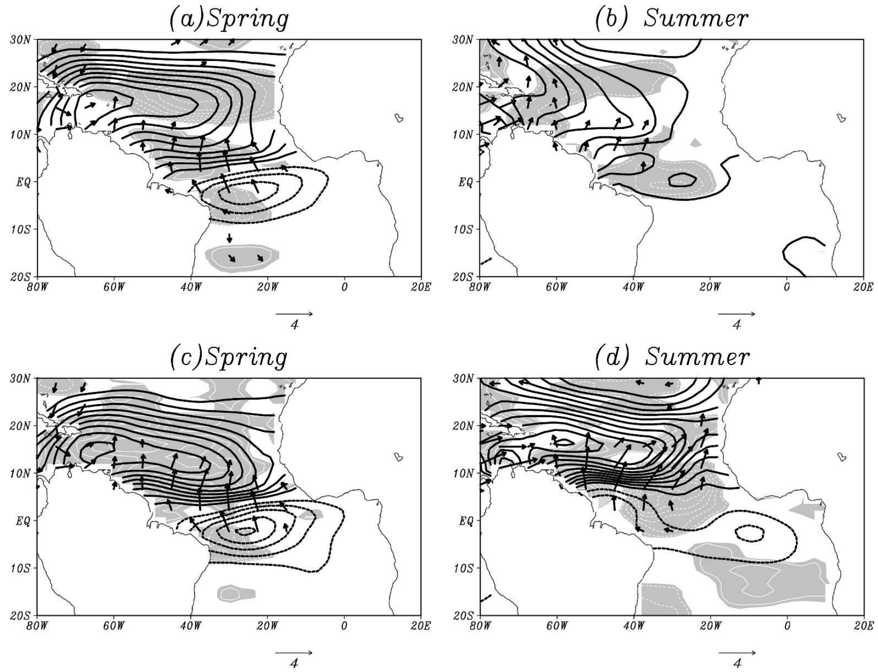

FIG. 4. SST (black contours with intervals at 0.2°C), surface wind (vectors, units are in m s^{-1}), and surface heat flux (white contours at 3 W m^{-2}; shading >5 W m^{-2}) in (a),(b) IV-NTA and (c),(d) PC-NTA. (a),(c) Spring (March–May) and (b),(d) summer (June–August).

and cooling, albeit weak, in the NTA (Fig. 5). In the following summer, the warming in the STA penetrates farther to the northern Tropics up to 10°N by following the seasonal migration of the ITCZ. Overall, the interhemispheric link from the STA to the NTA is weaker than that from the NTA to the STA.

In summary, both the IV-NTA and the PC-NTA suggest that the interhemispheric interaction over the tropical Atlantic are dominated by the WES feedback and mediated by the seasonal migration of the ITCZ and the mean oceanic advection. The interhemispheric seesaw appears to be robust in the spring season, consistent with the observational study by Enfield et al. (1999), although this interhemispheric seesaw remains elusive in both observations (e.g., Houghton and Tourre 1992) and modeling studies (e.g., Dommenget and Latif 2000). One major challenge to isolate the dynamics of this so-called tropical Atlantic dipole is that the tropical Atlantic is subject to multiple remote forcing including both ENSO and NAO that may potentially mask out this weakly coupled interhemispheric mode. In our fully coupled simulation, the interhemispheric link is also weak, similar to most of coupled GCM simulations (e.g., Frankignoul et al. 2004). In our experiments here, remote forcing is essentially eliminated through the ensemble average; therefore, this weakly coupled interhemispheric mode becomes more apparent.

b. *Tropical–extratropical teleconnection*

Previous studies have used AGCM and/or AGCM coupled to a mixed layer ocean to assess the influence of tropical Atlantic SST on the North Atlantic climate. These approaches, although useful in understanding the atmospheric dynamic process, are not sufficient to address the impacts of the tropical Atlantic SST on the North Atlantic climate. First, the tropical–extratropical teleconnection exhibits a strong seasonality that requires a naturally changing tropical Atlantic SST forcing to simulate the seasonality of this teleconnection. Second, over the extratropics, a fully coupled ocean–atmosphere system is essential to simulate a correct atmospheric response to underlying SST changes (Liu and Wu 2004). To this end, the IV experiment is a natural modeling setting, which allows us to examine not only the seasonality of the tropical–extratropical teleconnection, but also coupled ocean–atmospheric response over the extratropics as well as its further feedback to the Tropics.

The IV-NTA experiment reveals a distinct seasonality of the tropical–extratropical atmospheric teleconnection (Figs. 6 and 7). In spring, the warm NTA SST

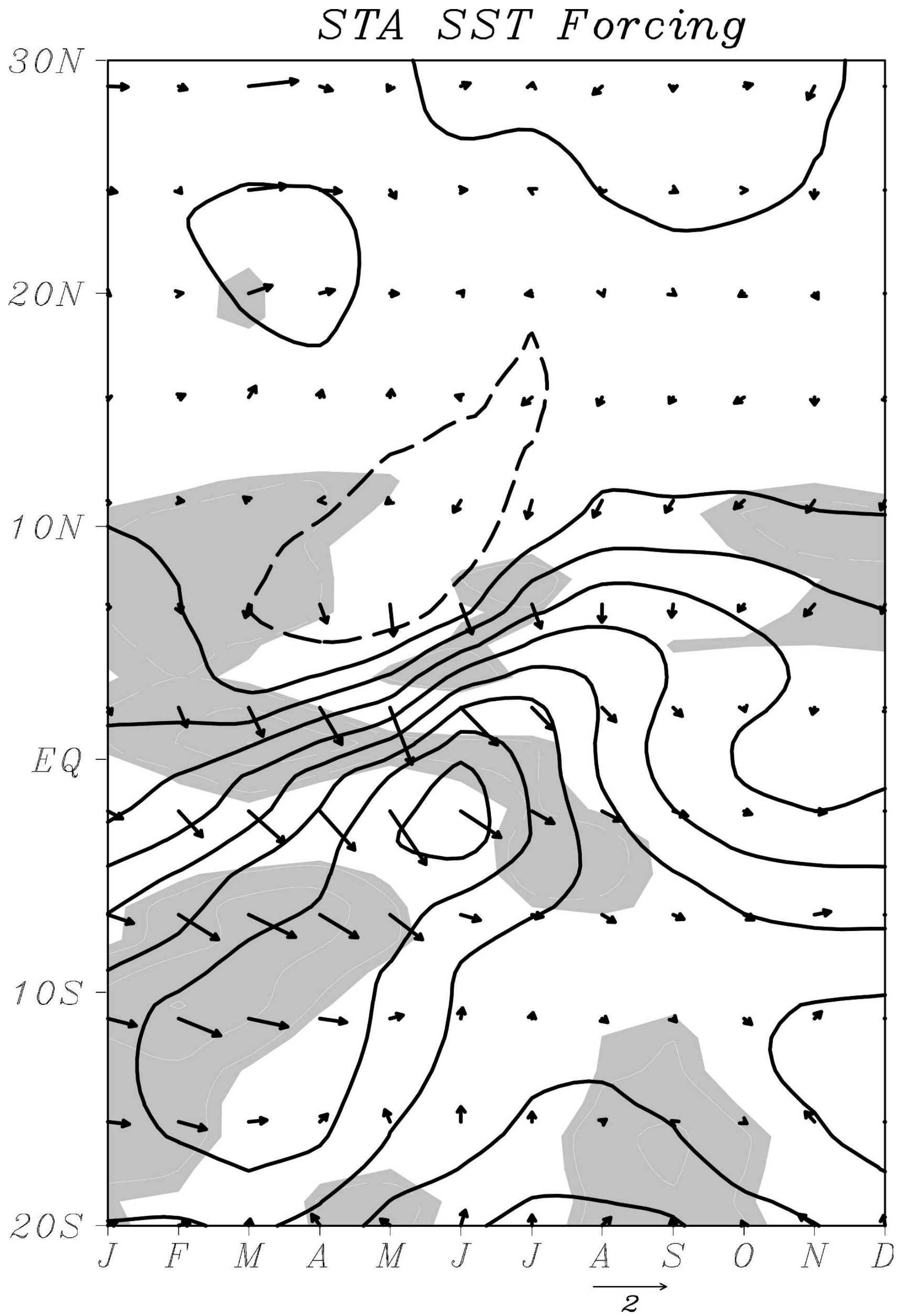

FIG. 5. Time–latitude section of SST (black contours at 0.2°C intervals), surface wind (vectors, units are in m s^{-1}), and surface heat flux (white contours at 3 W m^{-2}; shading >5 W m^{-2}) zonally averaged over (60°W–10°E) in the experiment PC-STA.

forces a local baroclinic response in the atmosphere with anomalous high pressure in the mid- and upper troposphere (Fig. 6a) and low pressure in the lower troposphere (not shown). The amplitude is about 20 gpm K^{-1} at Z500. Over the extratropical North Atlantic, the atmospheric response exhibits a negative NAO-like pattern with a high over Greenland and a low over the western subtropical North Atlantic. The amplitude, measured by the difference between two centers, is about 20 gpm K^{-1} (per degree in NTA) at Z500. The

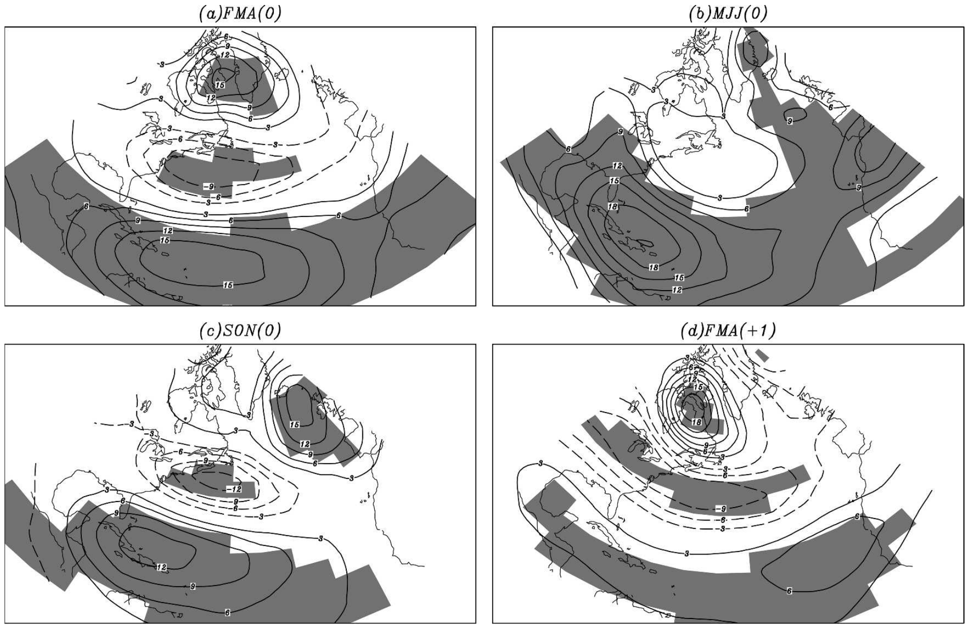

FIG. 6. The Z500 geopotential height (units are gpm) in IV-NTA: (a) February–April (+0), (b) May–July (+0), (c) September–November (+0), and (d) February–April (+1). Shaded areas exceed the 90% significance limit using statistics.

response is nearly equivalent barotropic. At the surface, the wind response is characterized by an anomalous cyclone over the North Atlantic that decelerates the midlatitude westerly, producing warming in the subpolar North Atlantic (Fig. 7a, the warming is weak partly due to an unrealistic mixed layer depth in this region). In the subtropics, the cold atmospheric advection by the anomalous cyclone generates cooling through an intensification of latent heat loss. Overall, in spring the NTA SST forces a coupled NAO-like response in the atmosphere and a dipole SST, albeit weak, over the extratropical North Atlantic. This is consistent with previous AGCM coupled with mixed layer ocean modeling studies (e.g., Okumura et al. 2001; Peng et al. 2005), although in their experiments SST forcing with a uniform polarity is prescribed over the entire tropical Atlantic including both the NTA and STA. The magnitudes here, however, appear to be weaker than theirs (about 30 gpm K^{-1} in Peng et al. 2005), which tend to be associated with the SST anomaly in the STA. The impacts of the STA SST will be discussed later.

In the following summer, the SST in the tropical Atlantic becomes substantially weaker with the center shifting to the Caribbean region (Fig. 7b). This northward shifting of the NTA SST is associated with the mean advection by the subtropical gyre (not shown). However, in spite of the decay of the SST, the tropical atmospheric response becomes even stronger than the late winter (Fig. 6b versus Fig. 6a), with the pattern also shifted to the west. The strong atmospheric response appears to be associated with the strong convection over the Caribbean region, which is part of the Western Hemisphere warm pool and sensitive to SST perturbation (Wang and Enfield 2001). Over the extratropical North Atlantic, the atmospheric response is very different from that in late winter, showing a wavy pattern emanating from the western tropical Atlantic extending to western Europe and the eastern subpolar North Atlantic, although the trough off Newfoundland is not apparent. This atmospheric response appears to favor a horseshoelike SST development in the extratropical North Atlantic (Fig. 7b). At the surface, anomalous southeasterly winds in the eastern subpolar North Atlantic warm up the ocean through reducing the turbulent heat flux out of the ocean. In the eastern North Atlantic along the North Africa coast, anomalous southwesterly winds diminish the northeast trade winds to produce warming. Overall, the SST response is reminiscent of the summer NAH pattern identified in the observations (Czaja and Frankignoul 2002). Clearly, the NAH here is a footprint of the changes of atmospheric circulation forced by SST in the NTA, consistent with the AGCM studies of Cassou et al. (2004).

In the following fall, the northeastward Rossby wave train extending from the western subtropics to the northeast subpolar Atlantic becomes more apparent (Fig. 6c), although both the tropical SST and thus the

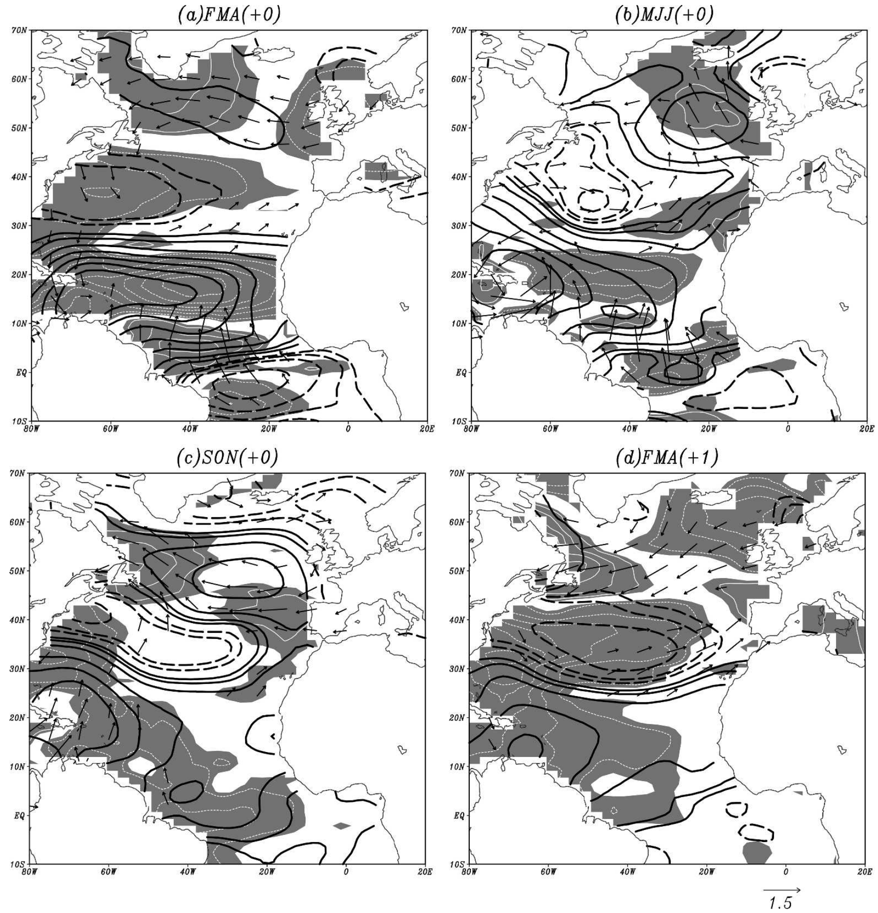

FIG. 7. SST (black contours), surface wind (vectors, units are in m s^{-1}), and surface heat flux (white contours at 5 W m^{-2}; shading >10 W m^{-2}) over the Atlantic sector in IV-NTA: (a) February–April (+0), (b) May–July (+0), (c) September–November (+0), and (d) February–April (+1). Contour intervals for SST are −0.6, −0.4, −0.3, −0.2, −0.1, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, and 1.2. The minimum wind speed is 0.6 m s^{-1}.

local atmospheric response diminishes (Fig. 7c). At the surface, the anomalous subpolar anticyclone also becomes more prominent, further slackening the midlatitude westerly to sustain the warming (Fig. 7c). The cooling in the western subtropics is also intensified due to the cold atmospheric advection by the anomalous cyclone off Newfoundland. Overall, the SST pattern in the fall remains similar to the summer, which is reminiscent of the observed NAH.

In the next winter, the local atmospheric response in the Tropics becomes much weaker due to the further weakening of the tropical SST (Fig. 6d). The extratropical atmospheric response, however, appears to be robust. Overall, the pattern shares some similarity to that in the previous winter, although the high pressure is shifted to the southwest of Greenland. At the surface, an anomalous cyclone is developed over the entire North Atlantic, which generates warming, albeit weak, in the western subpolar North Atlantic and cooling in the subtropical North Atlantic through weakening of midlatitude westerly and anomalous cold atmospheric advection, respectively (Fig. 7d). In general, from summer to winter, the pattern of North Atlantic SST exhibits a shift from a horseshoe to a dipole, coupled with a shift of atmospheric pattern from a northeastward wave train to an NAO-like dipole.

The IV-NTA experiment here explicitly demonstrates a distinctive seasonality of the influences of the NTA SST on the extratropical North Atlantic coupled ocean–atmosphere interaction. The NTA SST can force a coupled NAO–dipole SST response over the extratropical North Atlantic in late winter, a coupled wave train–horseshoe SST response in the following summer and fall, and a recurrence of the NAO in the next winter. The response changing from a Rossby–wave train pattern in the early winter to a NAO-like

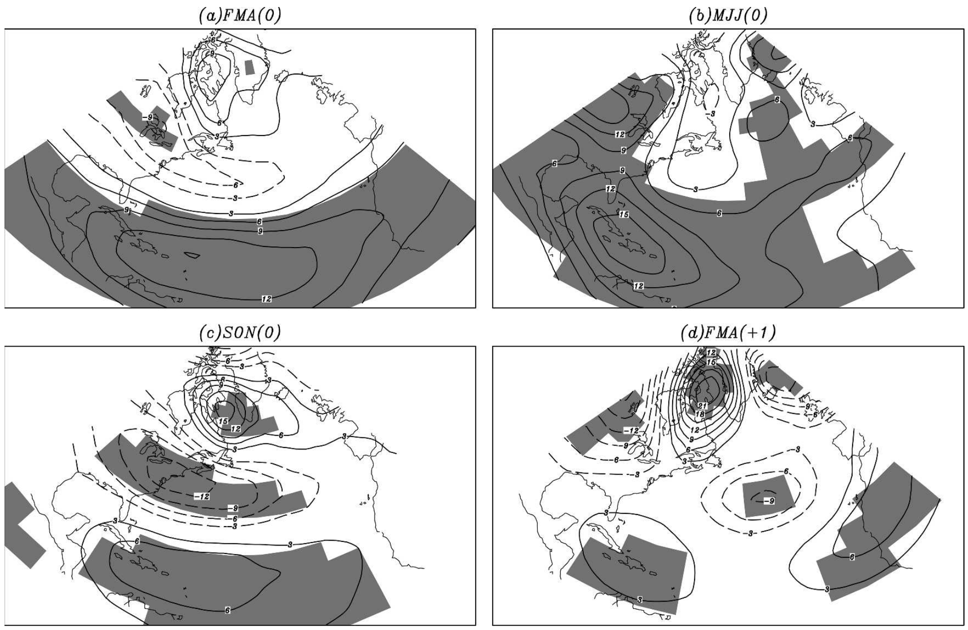

FIG. 8. Z500 geopotential height (gpm) in IVPC-NTA (no air–sea coupling in the extratropical North Atlantic): (a) February–April (0), (b) May–July (0), (c) September–November (0), and (d) February–April (+1).

pattern in late winter here is consistent with the modeling results of Peng et al. (2005), in which the tropical SST plays a dominant role. However, in our experiment here, it remains possible that such a shift as well as the recurrence of the next winter's NAO may be also associated with the extratropical SST forced by the tropical SST. Observational statistical analysis (Czaja and Frankignoul 2002) and AGCM modeling studies (Cassou et al. 2004) suggest an important role of the summer-to-fall NAH in sustaining the winter-to-winter NAO persistency.

To further assess the role of extratropical air–sea coupling in the atmospheric response, another set of ensemble experiments is performed, which is similar to the IV-NTA except that air–sea coupling over the extratropical North Atlantic is disabled. In this case, the feedback of the extratropical North Atlantic SST (forced by the tropical Atlantic) to the atmosphere is eliminated. This experiment is referred to as IVPC-NTA.

In the IVPC-NTA, the atmospheric response also exhibits a distinctive seasonality, but differs from that in the IV-NTA (Fig. 8). In early spring, while the tropical response remains similar to that in the IV-NTA, the extratropical atmospheric response appears to be much weaker (Fig. 8a versus Fig. 6a), suggesting the important role of air–sea coupling in establishing the atmospheric response over the extratropics (e.g., Liu and Wu 2004). In the following summer, the atmospheric response demonstrates a wavy pattern emanating from the western tropical Atlantic toward the east of Greenland, which remains similar to that in the IV-NTA (Fig. 8b versus Fig. 6b). In general, the extratropical atmospheric response in summer is weak, partly because of weak atmospheric eddy activity and a lack of coherent atmospheric internal variability modes. Therefore, in summer the effect of the air–sea coupling on the atmospheric response is minimal. In the following fall, the wave train becomes more apparent as that in the IV-NTA, although the high-latitude ridge is somewhat shifted to the east of Greenland (Fig. 8c versus Fig. 6c). The amplitudes of the atmospheric response in the extratropics are comparable to those in the IV-NTA, in spite of a reduction in the Tropics that may be attributed to the reduced impacts of the resulting extratropical atmospheric response in the previous seasons. The pattern persists into the next winter, although the subtropical trough is somewhat shifted to the central Atlantic (Fig. 8d versus Fig. 6d).

In summary, the IVPC-NTA experiment suggests that the extratropical air–sea coupling is not essential for establishing the seasonality of the atmospheric response to the tropical SST, but it can nevertheless enhance the winter-to-winter NAO persistency.

The above experiment only focuses on the NTA. The observed pan-Atlantic SST anomaly also has expressions in the STA. To assess the impacts of the STA SST, we analyzed the extratropical North Atlantic coupled

FIG. 9. Z500 geopotential height (gpm) in PC-STA: (a) February–April, (b) May–July, and (c) September–November.

ocean–atmosphere response in the PC-STA experiment. In spring, the warm STA SST also forces a NAO-like response over the extratropical North Atlantic (Fig. 9a), which has the same pattern and polarities as that forced by the warm NTA SST, although the statistic significance is weaker. In the following summer, the response is generally negligible, seemingly due to a lack of anomalous convection over the Caribbean region (Fig. 9b). In the following fall, a similar wave pattern appears, although the subtropical lobe shifts far west to the North American continent (Fig. 9c versus Fig. 6c). This response appears to be associated with the northward penetration of the warm STA SST in this season (Fig. 5), which induces anomalous tropical convection. The atmospheric response in the next winter is largely identical to that in the previous winter due to a fixed SST forcing (not shown). In short, the warm SST in the STA forces a similar atmospheric response in the extratropical North Atlantic in both early and late winter as those forced by the warm SST in the NTA. Therefore, an SST dipole in the tropical Atlantic may not be able to force a significant response over the extratropics. This may partly explain the weaker response in our IV-NTA experiment when compared with other modeling studies in which an SST anomaly with a uniform polarity is prescribed over the entire tropical Atlantic (e.g., Peng et al. 2005).

c. *Tropical Atlantic–tropical Pacific teleconnection*

Past studies have identified the atmospheric teleconnection from the tropical Pacific to the tropical Atlantic. Less attention has been paid to the adverse teleconnection from the tropical Atlantic to the tropical Pacific. Recent coupled modeling studies (e.g., Dong and Sutton 2002; Zhang and Delworth 2005) indicate there is a potential link from the Atlantic to the Pacific through the atmospheric bridge and/or oceanic Kelvin and Rossby wave teleconnection (e.g., Timmermann et al. 2005). Here, we will demonstrate an efficient tropical atmospheric bridge from the Atlantic to the tropical Pacific.

The IV-NTA experiment explicitly demonstrates that the tropical Atlantic SST anomaly can induce significant response over the tropical Pacific through the atmospheric teleconnection (Fig. 10). In spring, while the NTA SST organizes an interhemispheric SST seesaw over the tropical Atlantic, the eastern tropical Pacific also forms a similar coupled ocean–atmosphere pattern (Fig. 10a). This coupled pattern is characterized by a warm SST anomaly north and a cold SST anomaly south of the equator, in conjunction with southerly cross-equatorial wind. In the following summer, the meridional SST dipole evolves into a zonal monopole, with a cooling straddling the eastern equatorial Pacific associated with anomalous easterlies (Fig. 10b). The cooling further intensifies and moves toward the west in the following fall (Fig. 10c). The amplitude of the cooling is about 1°C in the western Pacific, which is about half of the initial NTA SST anomaly.

What are the mechanisms linking the tropical Atlantic and tropical Pacific? In the spring season, the warm NTA SST anomaly induces a surface low over the western tropical Atlantic with the center located over the Caribbean region (Fig. 11a). This surface low is associ-

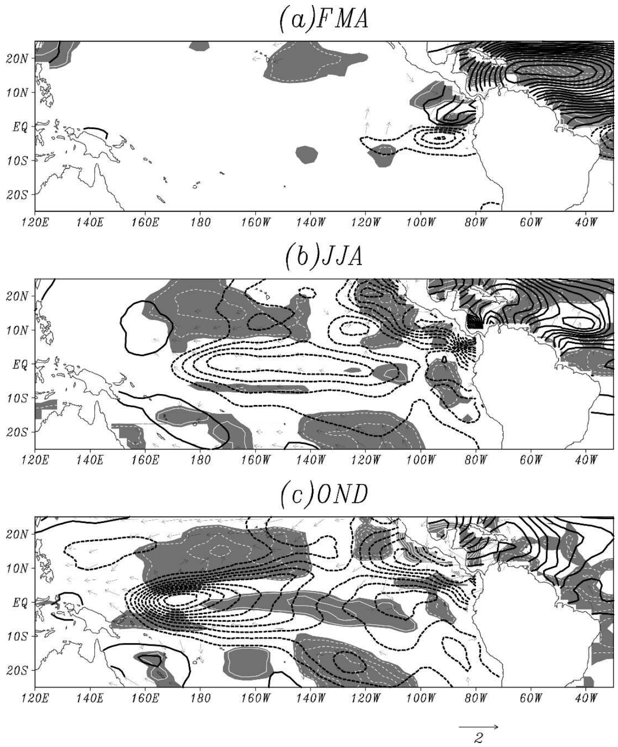

FIG. 10. Tropical SST (black contours at 0.1°C intervals), surface wind (vectors, units are in m s^{-1}), and surface heat flux (white contours at 3 W m^{-2}; shading >5 W m^{-2}) in IV-NTA: (a) February–April, (b) June–August, and (c) October–December.

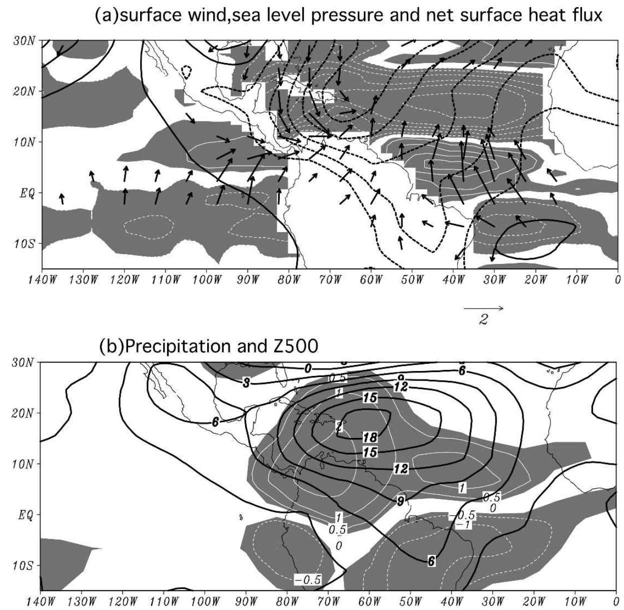

FIG. 11. (a) March–May surface wind (vectors, units are in m s^{-1}), sea level pressure (black contours with 0.3 mb), and surface heat flux (contour intervals are −20, −15, −10, −5, −2, 2, 5, 10, 15, and 20 W m^{-2}; shading >2 W m^{-2} in IV-NTA. (b) March–May precipitation (mm day^{-1}, shading >0.3 mm day^{-1}) and Z500 (gpm).

ated with anomalous atmospheric convection fueled by the warm NTA, as shown by wetter-than-average condition over Central America (Fig. 11b). The low pressure induces anomalous westerlies in the northeastern equatorial Pacific, which decelerate the northeast trades in spring, leading to a reduction of turbulent heat flux out, and thus warming of the ocean (Fig. 11a). Following the same mechanism in the tropical Atlantic, the warming north of the equator sets up a southward meridional pressure gradient, inducing southerly cross-equatorial winds that accelerate the southeast trades, and that leads to a cooling in the south. In summer, the ITCZ moves to its northernmost location and the northern deep Tropics is now dominated by the southeast trades (Fig. 2a). The anomalous southerly cross-equatorial winds intensify the turbulent heat loss in the northern deep Tropics, which favors a northward extension of the cooling pole. The extended cooling in the equatorial region can be further amplified by the positive equatorial Bjerknes feedback. It can be seen that the surface heat flux does not contribute to the zonal development of the cooling. Indeed, the heat flux tends to damp the SST in fall, suggesting the important role of the ocean subsurface dynamics, presumably the enhanced equatorial upwelling by the accelerated easterly (Fig. 10c). It should be noted that the cooling west of the date line is somewhat exaggerated due to an unrealistic shoaling of the model thermocline in this season, partly because of an incorporation of the shortwave penetration scheme (Fig. 10c).

The IV-NTA experiment indicates that the formation of the meridional SST dipole in spring over the eastern equatorial Pacific and its subsequent switch to the zonal SST monopole, or ENSO-like pattern, is controlled by the positive WES and Bjerknes feedbacks meditated by the seasonal migration of the mean ITCZ. To further test the intrinsic mechanisms of the Pacific SST development, we performed two additional sets of experiments, in which a warm mixed layer temperature anomaly is initiated in the northeastern and southeastern subtropical (5°–25° latitudinal band) Pacific, respectively. We refer to these two experiments as IV-NTP and IV-STP. The IV-NTP and IV-STP essentially capture the major features simulated in the IV-NTA experiment. In the IV-NTP experiment, the warm NTP SST anomaly immediately creates a cold SST anomaly south of the equator coupled with anomalous southerly cross-equatorial winds in spring, forming a meridional SST dipole (Fig. 12a). This meridional dipole mode, similar to that in the tropical Atlantic (Chiang and Vimont 2004), is organized by the positive WES feedback,

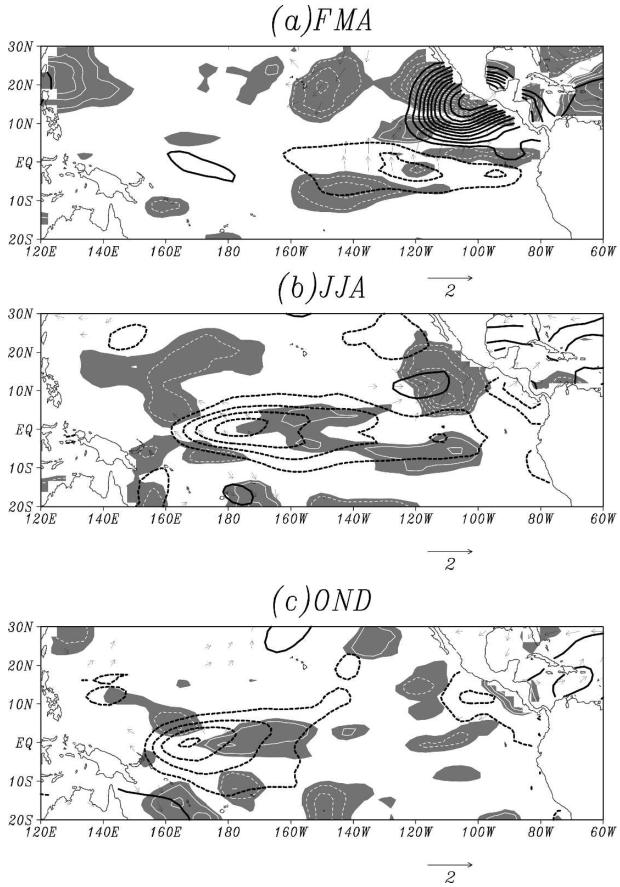

FIG. 12. Tropical SST (black contours at 0.1°C intervals), surface wind (vectors, units are in m s^{-1}), and surface heat flux (white contours at 2 W m^{-2}; shading >3 W m^{-2}) in IV-NTP: (a) February–April, (b) June–August, and (c) October–December.

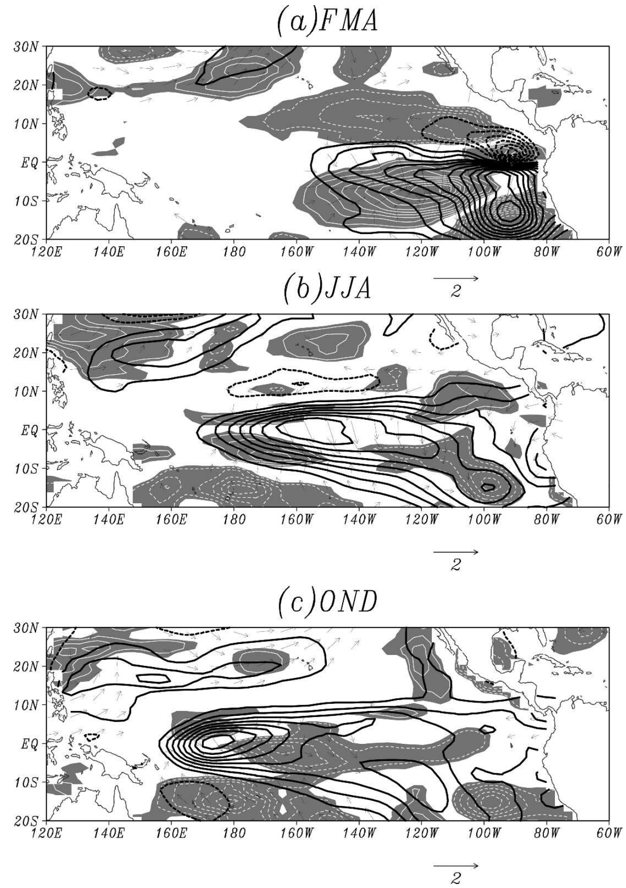

FIG. 13. Same as in Fig. 12, but for the experiment IV-STP.

thus displays a sharp contrast to the zonal ENSO mode that is organized by the positive Bjerknes feedback. In the following season, the southern SST lobe grows quickly in contrast to a fast decay of the northern SST lobe (Fig. 12b). As in the IV-NTA experiment, the equatorial region now is dominated by the cold SST anomalies that propagate toward the west (Fig. 12c). In the IV-STP experiment, the warm SST anomaly quickly extends to the equatorial region and creates cold SST anomalies north of the equator in conjunction with anomalous northerly cross-equatorial winds (Fig. 13a). The warm SST anomaly extends farther to the west coupled with some weak cold SST anomalies in its northern flank through the WES feedback (Figs. 13b,c).

In summary, these two experiments confirm the role of the WES feedback in generating the meridional SST dipole in the eastern equatorial Pacific and the role of the seasonal migration of the ITCZ in conjunction with the equatorial Bjerknes feedback in its subsequent transition to the ENSO-like zonal pattern.

4. Summary and discussion

In this paper, the atmospheric teleconnections of the tropical Atlantic SST variability are investigated in a series of coupled ocean–atmosphere modeling experiments. It is found that the tropical Atlantic climate not only displays an apparent interhemispheric link, but also significantly influences the extratropical North Atlantic and the tropical Pacific climate. Within the tropical Atlantic, the coupled ocean–atmosphere interaction exhibits an interhemispheric link in the spring, controlled by the wind–evaporative–SST (WES) feedback and the seasonal migration of the ITCZ. Over the North Atlantic, the tropical Atlantic SST can force a coupled NAO–dipole SST response in spring, that changes to a Rossby wave train–horseshoe SST response in the following summer and fall, and a recurrence of the NAO in the next winter. The model also demonstrates the resulting extratropical SST anomalies may not be necessary for the recurrence of the next winter's NAO, but can contribute to the extratropical atmospheric response constructively. While the de-

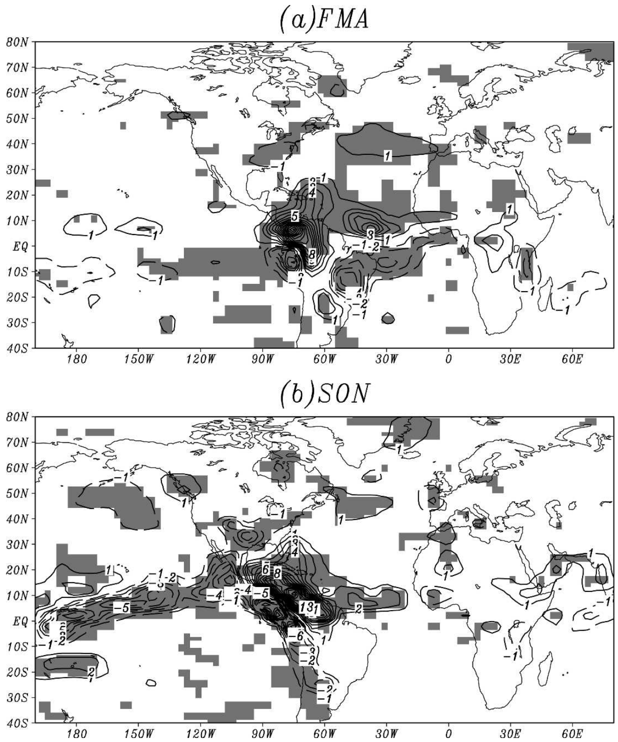

FIG. 14. Anomalous precipitation (cm month^{-1}) in IV-NTA: (a) February–April and (b) September–November. Shaded areas exceed the 90% significance limit using t statistics.

tailed mechanisms of the seasonal changes of the atmospheric response are beyond the scope of the current study, it appears that the seasonal marching of the atmospheric mean climatology, the modulation of the interaction between synoptic eddies and stationary waves (e.g., Luo et al. 2007a,b), and the local air–sea coupling are among contributing factors. Over the Pacific, the model demonstrates that the NTA SST can drive a meridional SST dipole in the eastern equatorial Pacific, that subsequently evolves into an ENSO-like zonal pattern dominated by the southern lobe.

The interhemispheric and cross-basin interactions induced by the NTA SST are also evident in the global precipitation (Fig. 14). In spring (Fig. 14a), the warm NTA induces a northward shift of the ITCZ, leading to a typical drier-than-average condition over the Nordeste and wetter-than-average, albeit weak, condition over the Sahel. The wetter-than-average condition over Central America is associated with anomalous convection due to the warm oceanic condition in this area. In general, the precipitation anomalies in mid- and high latitudes are negligible. In the following summer and fall (Fig. 14b), the precipitation over the Caribbean region is substantially intensified, while drier-than-average condition spreads over the majority of the central America. The drier-than-average condition also occurs in the southeastern part of the United States, associated with the locally divergent surface circulation (not shown). In the eastern equatorial Pacific, the developing cold SST anomaly forces the vertical stabilization of the tropical atmosphere, leading to negative precipitation anomalies in this region.

Past studies have recognized the significant impacts of NAO and ENSO on the tropical Atlantic climate (e.g., Nobre and Shukla 1996; Enfield and Mayer 1997; Saravanan and Chang 2000). Our studies here systematically examine the adverse impacts of the tropical Atlantic on the NAO and ENSO. In our experiments, the imposed temperature anomaly in the tropical Atlantic can be generated by some external forcing including both ENSO and NAO, or coupled ocean–atmosphere interaction locally in the tropical Atlantic. Therefore, the study extends the previous studies by looking at the further feedbacks of the tropical Atlantic to these external forcing modes.

The influence of the NTA SST on the tropical Pacific and the North Atlantic may have some implications for the interaction between ENSO and NAO. Past studies have documented the influence of ENSO on NAO. Our study here further implies that NAO can affect ENSO by creating SST anomalies over the NTA.

The atmospheric teleconnection from the tropical Atlantic to the tropical Pacific may potentially affect the life cycle of ENSO. In observations, El Niño events occur about every 3–8 yr, but most of El Niño events usually cease in the next spring and are followed by a La Niña event. Here, the negative feedback externally imposed from the NTA in the spring season, as an addition to the negative feedback internal to the equatorial Pacific, can help terminate an El Niño and subsequently trigger a La Niña event.

Our study also has some implications for the recent coupled GCM experiments of studying the abrupt climate changes. In these experiments, an El Niño–like pattern in the tropical Pacific is associated with the Atlantic interhemispheric seesaw resulting from a weakening of the Atlantic meridional overturning circulation forced by a large freshwater flux in the high latitudes of the North Atlantic (e.g., Dong and Sutton 2002; Zhang and Delworth 2005). This study appears to support this cross-basin teleconnection, and suggests that the teleconnection from the North Atlantic to the tropical Pacific is largely mediated by the seasonal migration of the mean ITCZ in association with the WES feedback. The model also indicates a strengthened (weakened) Asian summer monsoon, likely attributed to the induced cooling (warming) in the tropical Pacific forced by a warm (cold) NTA SST.

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