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Response of the Asian Summer Monsoon to Weakening of Atlantic Thermohaline Circulation

LU Riyu*[1,2] (陆日宇) and Buwen DONG[3,4]

[1] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[2] *Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[3] *Walker Institute for Climate System Research, University of Reading, Reading, UK*

[4] *National Centre for Atmospheric Science-Climate, Reading, UK*

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ABSTRACT

Various paleoclimate records have shown that the Asian monsoon was punctuated by numerous sub-orbital time-scale events, and these events were coeval with those that happened in the North Atlantic. This study investigates the Asian summer monsoon responses to the Atlantic Ocean forcing by applying an additional freshwater flux into the North Atlantic. The simulated results indicate that the cold North Atlantic and warm South Atlantic induced by the weakened Atlantic thermohaline circulation (THC) due to the freshwater flux lead to significantly suppressed Asian summer monsoon. The authors analyzed the detailed processes of the Atlantic Ocean forcing on the Asian summer monsoon, and found that the atmospheric teleconnection in the eastern and central North Pacific and the atmosphere-ocean interaction in the tropical North Pacific play the most crucial role. Enhanced precipitation in the subtropical North Pacific extends the effects of Atlantic Ocean forcing from the eastern Pacific into the western Pacific, and the atmosphere-ocean interaction in the tropical Pacific and Indian Ocean intensifies the circulation and precipitation anomalies in the Pacific and East Asia.

Key words: Asian summer monsoon, Atlantic thermohaline circulation, dynamical process

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1. Introduction

The Asian monsoon, which includes both the East Asian and South Asian monsoons, is an important component of global atmospheric circulation and plays a significant role in the global hydrological and energy cycles. This monsoon system exhibits variability on various time scales and the understanding of this variability remains a challenging work. The monsoon is of great socioeconomic importance since it influences two-thirds of the world population inhabiting tropical Asia.

The paleo records of the Asian monsoon are punctuated by numerous centennial- to millennial-scale events, much shorter than orbital time scales (Sirocko et al., 1993; Gupta et al., 2003; Fleitmann et al., 2003). Recent studies of stalagmite records show that on sub-orbital time scales, there is a close relationship between North Atlantic climate and the Asian summer monsoon. The stalagmite records from Hulu Cave (or Tangshan Cave) in East China and Dongge Cave in South China all show striking similarities with the Greenland ice core records (Wang et al., 2001a; Gupta et al., 2003; Zhao et al., 2003; Dykoski et al., 2005). The intensity of the East Asian monsoon switched in parallel with the abrupt transitions separating the Bolling-Allerod, Younger Dryas, and pre-Boreal climatic reversals. Dykoski et al. (2005) compared their monsoon record from Dongge Cave with the Indian monsoon record obtained from the stalag-

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*Corresponding author: LU Riyu, lr@mail.iap.ac.cn mites of Oman (Fleitmann et al., 2003), and found a close correspondence between these two records.

These sites represent a broad region of the Asian summer monsoon. Hulu Cave (32°N, 119°E) is under the direct influence of the prevailing East Asian monsoon, and Dongge Cave is in a region of China affected by both the Indian monsoon and the East Asian monsoon (Ding et al., 2004). Therefore, these earlier studies indicate that there is a close relationship between North Atlantic climate and precipitation over a broad region of the Asian monsoon system.

Furthermore, there are other proxy records as well indicating a link between the variations in the North Atlantic climate and the Asian summer monsoon. For instance, Wang et al. (1999) analyzed the sediment records from the northern South China Sea, which may serve for monitoring past variations in fluvial discharge and monsoonal precipitation in South China, and found significant centennial to millennial-scale cold and dry, and warm and humid spells in the records. They suggested that these spells are coeval with the variations in the Indian monsoon, and with cold Heinrich and warm Dansgaard-Oeschger events as recorded in Greenland ice cores. In addition, Guo et al. (1996) suggested that climate events in the Chinese Loess Plateau, which is located at the northern edge of the East Asian summer monsoon system, can be temporally correlated with the North Atlantic Heinrich events.

There is evidence, on the shorter time scales, showing that Atlantic Ocean forcing affects the summer climate in the western North Pacific and the Asian summer monsoon. Based on the simulated results by an AGCM, Lu and Dong (2005) suggested that through tropical stationary waves, Atlantic SST anomalies in 1998 might have affected the atmospheric circulation and precipitation in the western North Pacific, which are closely related to the East Asian summer monsoon (e.g., Wang et al., 2001b; Lu, 2004). On decadal-multidecadal time scale, the Atlantic Multidecadal Oscillation (AMO) also influences the Asian summer monsoon (Goswami et al., 2006; Lu et al., 2006; Zhang and Delworth, 2006). The idea that large inputs of freshwater due to the melting of ice caps and discharge of freshwater stored in huge North American lakes strongly reduced the Atlantic thermohaline circulation (THC) is the consensual hypothesis for North Atlantic events such as the Younger Dryas. Using a coupled atmosphere-ocean model, Zhang and Delworth (2005) simulated weakened Indian and East Asian summer monsoons in response to a weakened Atlantic THC. However, the mechanisms through which the Atlantic Ocean influences the Asian summer monsoon are unclear and need to be elucidated. Therefore, in this study, we perform a modeling experiment to investigate the impact of the weakened THC due to anomalous freshwater flux in the North Atlantic on the Asian summer monsoon, and discuss the relevant mechanisms responsible for the impact.

In section 2, the model and experimental design are described. The boreal summer climate responses over the tropical Pacific and Asian monsoon region are documented in section 3. The physical mechanisms involved for these remote responses are elucidated in section 4 and a summary is given in section 5.

2. Model and experiments

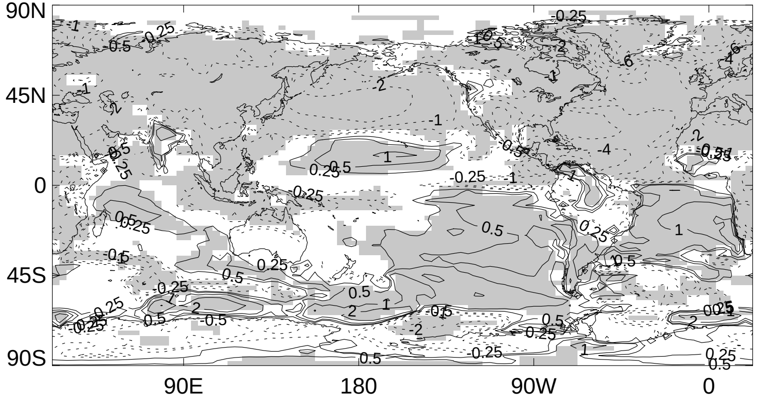
The model used in this study is a coupled atmosphere-ocean general circulation model developed at the Hadley Centre (HadCM3). The atmospheric component of HadCM3 has 19 levels with a horizontal resolution of 2.5° (lat)×3.75° (lon) (Pope et al., 2000), and the oceanic component has 20 levels with a horizontal resolution of 1.25° by 1.25° (Gordon et al., 2000). The two components are coupled once a day. The model does not require flux corrections to maintain a stable climate. The mean climate and its stability in a 1000-yr control simulation are discussed in Gordon et al. (2000).

A water-hosing experiment is conducted in which an extra freshwater flux of 1.0 Sv is applied for 100 years to the North Atlantic between 50°N and 70°N. The initial condition is taken from the 1000 year control simulation of the coupled model (Gordon et al., 2000). The external freshwater forcing is then switched off after model year 100 and the model was integrated for another 100 years. The differences in the results between the water-hosing and control experiments allow us to assess the response of the mean climate change in the Asian monsoon region to the anomalous Atlantic Ocean state. We analyze the mean results of the first 100 years.

3. Results

The inputs of anomalous external freshwater lead to remarkable changes of SST in the Atlantic in boreal summer (Fig. 1a). The SST anomalies show a dipolar pattern in the Atlantic: strong cooling in the North Atlantic and warming in the South Atlantic. The cooling in the North Atlantic is much stronger than the warming in the South Atlantic. This pattern of SST anomalies can be expected as a result of THC weakening induced by the anomalous external freshwater flux in the North Atlantic. In the model's simulation, the THC slows down rapidly and weakens by about 75% after 50 years, in response to the freshwater input, and

(a) Surface temperature anomalies



(b) Precipitation anomalies

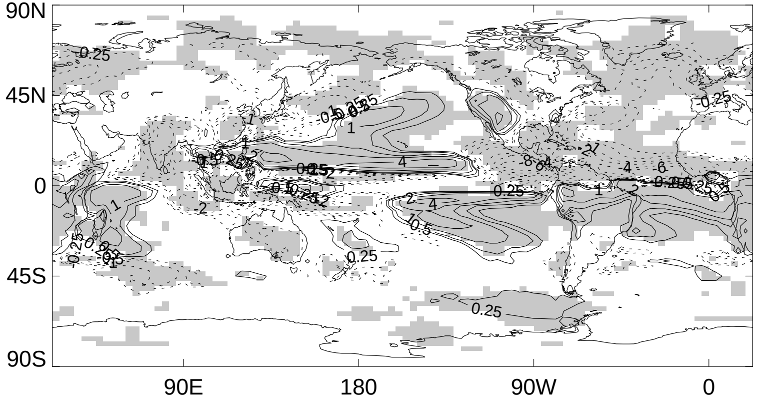


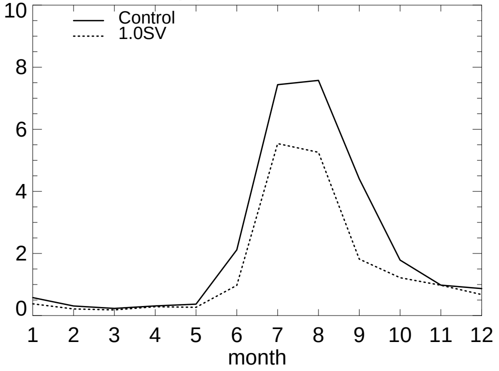
Fig. 1. The climatological mean anomalies in JJA between the 1 Sv and control experiments. (a) Surface temperature (°C), and (b) precipitation (mm d^{-1}). Shading indicates regions where anomalies are significant above 95% confidence level using t-test. Contours are ±0.25°C, ±0.5°C, ±1°C, ±2°C, ±4°C, ±6°C and ±8°C in (a) and ±0.25, ±0.5, ±1, ±2, ±4, ±6 mm d^{-1} and ±8 mm d^{-1} in (b).

a very slow recovery starts from year 150 (Dong and Sutton, 2007). Outside the Atlantic, there are also significant surface temperature anomalies. Particularly, surface temperatures are decreased in the western Pacific, maritime continents and the northern Indian Ocean by 0.25°C–0.5°C. Cooler and warmer SSTs are induced over the eastern Pacific north and south of the equator, respectively. Generally, surface temperatures tend to decrease in the Northern Hemisphere and increase in the Southern Hemisphere. However, there are some places in the Northern Hemisphere, including the tropical central North Pacific and Indian subcontinent, where temperatures increase.

The precipitation anomalies (Fig. 1b) in the tropics over oceans generally correspond well to the underlying SST anomalies. The dipolar pattern of SST anomalies in the Atlantic Ocean induces suppressed precipitation in the North Atlantic and enhanced precipitation in the South Atlantic, with the largest precipitation anomalies appearing in the tropical North Atlantic. This pattern of precipitation anomalies in the tropical Atlantic indicates a southward shift and weakening of the ITCZ in the Atlantic. These precipitation anomalies in the Atlantic extend westward into the American continent and the eastern tropical Pacific north of the equator. Figure 1b also shows significantly suppressed precipitation (1.0–2.0 mm d^{-1}) over South and East Asia. These anomalies correspond to a decrease of about 20%–40% relative to the current climatology both in model and in observations, indicating a much weakened Asian summer monsoon. The negative precipitation anomalies in East Asia extend northeastward into the North Pacific. Actually, this band of negative precipitation anomalies from South China to the central North Pacific concurs with the summertime climatological rain band in the model (not shown), which also indicates a weakening of the whole East Asian summer monsoon. In the tropical western and central North Pacific, precipitations are enhanced. Eastward to the negative precipitation anomaly extending from the subtropical western North Pacific northeastward into the central North Pacific is a positive precipitation anomaly, which is connected with the tropical positive precipitation anomalies. The enhanced precipitations in the South China Sea, the Philippine Sea and the extratropical North Pacific correspond to the underlying cooler SSTs, implying that these changes in precipitation are not a direct response to local SST anomalies. The suppressed precipitation in the maritime continent, northern and southeast Indian Ocean, and the enhanced precipitation in the Southwest Indian Ocean are associated with the underlying cold and warm SST anomalies, implying local coupled responses to remote forcing due to the weakened THC.

The seasonal evolutions in precipitation over India and East Asia are illustrated in Fig. 2. It indicates that the largest decrease in precipitation due to weakened THC occurs from July to September over India and from June to September over East Asia. The large decrease of precipitation in September over India indicates an early withdrawal of the Indian summer monsoon. The precipitation anomalies exhibit a clear dependence on seasons. This seasonality will be discussed further in the next section.

(a) Over India



(b) Over east Asia

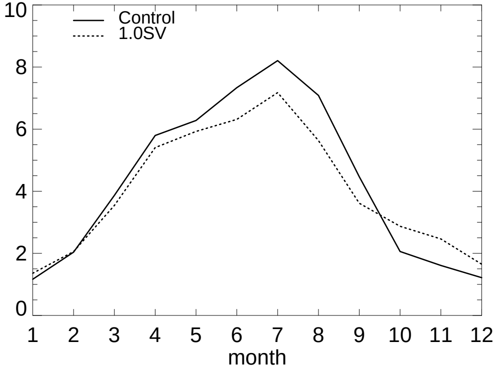
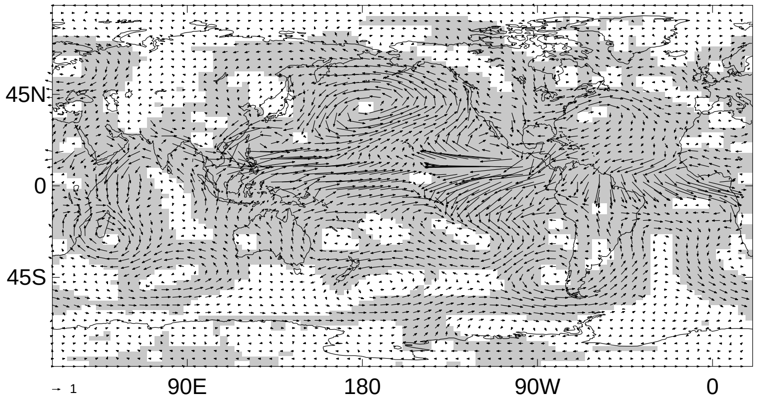


Fig. 2. The seasonal evolution of area averaged (over land points only) precipitation (mm d^{-1}). (a) India (10°–25°N, 70°–90°E) and (b) East Asia (20°–35°N, 105°–120°E).

The cold SST anomalies in the North Atlantic and warm SST anomalies in the South Atlantic induce significant lower tropospheric northerly anomalies in the equatorial Atlantic and in northern South America (Fig. 3a). In addition, there are anticyclonic anomalies over the subtropical North Atlantic and the eastern subtropical North Pacific, associated with the strongly suppressed precipitations in the tropical North Atlantic, Central America and eastern subtropical North Pacific (Fig. 1b), which can be explained by the theory of Gill (1980). Interestingly, the wind anomalies in the equatorial Pacific and North Pacific are larger than the local responses in the Atlantic. There is a cyclonic circulation anomaly over the North Pacific, extending into the tropical western North Pacific and the South China Sea. Associated with this cyclonic anomaly and the anticyclonic anomaly over the subtropical eastern North Pacific, there are strong westerly anomalies in the tropical western and central Pacific, and easterly anomalies in the tropical eastern Pacific, leading to anomalous convergence at about 150°W. The anomalous cyclonic circulation over the western North Pacific indicates a weakening of the subtropical high over the northwestern tropical Pacific. Associated with this is a weakening East Asian summer monsoon circulation. This, in turn, leads to weakened precipitation over East Asia. The anomalous northeasterlies over the Arabian Sea indicate a weakened Somali jet and therefore a weakened Indian summer monsoon circulation.

The 200-hPa horizontal wind anomalies (Fig. 3b), together with those at 850 hPa, indicate baroclinic structures over the subtropical eastern North Pacific and western North Pacific, suggesting that these lower and upper tropospheric circulation anomalies are a direct response to anomalous heating induced by SST anomalies. In the mid-latitude North Pacific, there is a cyclonic anomaly in the upper troposphere, indicating that this extratropical response is barotropic.

The Atlantic Ocean forcing also induces significant changes in specific humidity. The specific humidity anomalies near the surface of oceans (Fig. 4a) correspond well to the underlying SST anomalies: specific humidity increases (decreases) over regions where anomalous SSTs are positive (negative). This suggests that warm (cold) SST anomalies lead to enhanced (suppressed) specific humidity. Over Asia, specific humidity decreases significantly, which is possibly resulting from the cold underlying surface temperatures


(a) 850 hPa wind anomalies

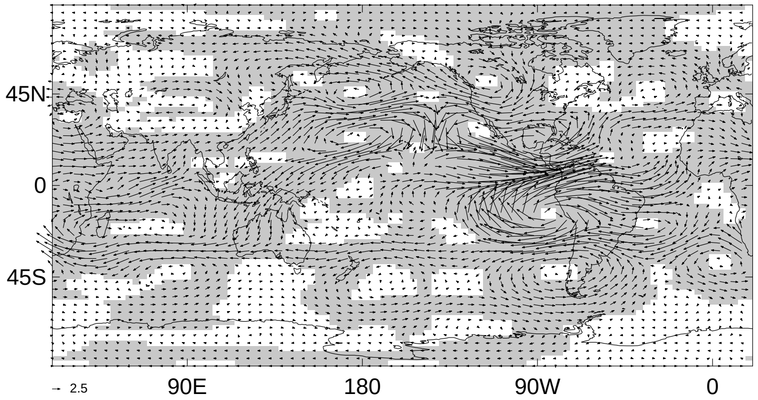

(b) 200 hPa wind anomalies

Fig. 3. The climatological mean wind anomalies (m s^{-1}) in JJA between the 1 Sv and control experiments. (a) at 850 hPa and (b) at 200 hPa. Shading indicates regions where either zonal wind or meridional wind anomalies are significant above 95% confidence level using *t*-test.

(Fig. 1a). With increasing altitude, the enhanced specific humidity corresponding to the warm SST anomalies in the tropical central North Pacific occupies a wider area, extending westward into the western Pacific and northeastward into the Northeast Pacific (Fig. 4b), and to a large extent, resembling the shape of the positive precipitation anomaly in the North Pacific. This extension of enhanced specific humidity with altitude suggests that anomalous lower tropospheric convergence of circulation (Fig. 5a) leads to moisture convergence (Fig. 5b) and also results in enhanced specific humidity at middle troposphere.

4. Processes of remote responses in the Pacific and Asian monsoon region

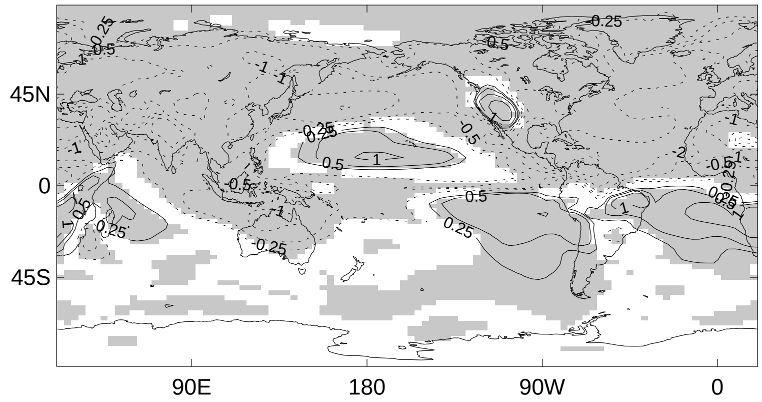
In the preceding section, it has been shown that the Atlantic Ocean forcing leads to substantial precipitation and circulation changes in the Pacific. These Pacific anomalies are as strong as the local responses in the Atlantic. In this section, we attempt to illustrate the possible physical mechanisms responsible for the remote responses in the Pacific and Asian monsoon region.

4.1 *Linkage between the western and eastern Pacific anomalies*

The strong negative precipitation anomaly in the tropical North Atlantic, induced by the dipolar pattern of the cold North Atlantic and warm South Atlantic SST anomalies, results in a lower-tropospheric anticyclonic anomaly in the tropical eastern North Pacific (Zhang and Delworth, 2005; Dong and Sutton, 2007). Particularly, Sutton and Hodson (2007) showed that the direct impact of Atlantic SST anomalies on the Pacific Basin is greatest in the boreal summer and autumn seasons; the reason being that in these seasons the latent heating anomalies are largest and furthest north, so they are more effective at driving atmospheric Rossby waves that can propagate westward into the Pacific.

The anomalous southwesterlies over the subtropi-

(a) 1000 hPa specific humidity anomalies



(b) 850 hPa specific humidity anomalies

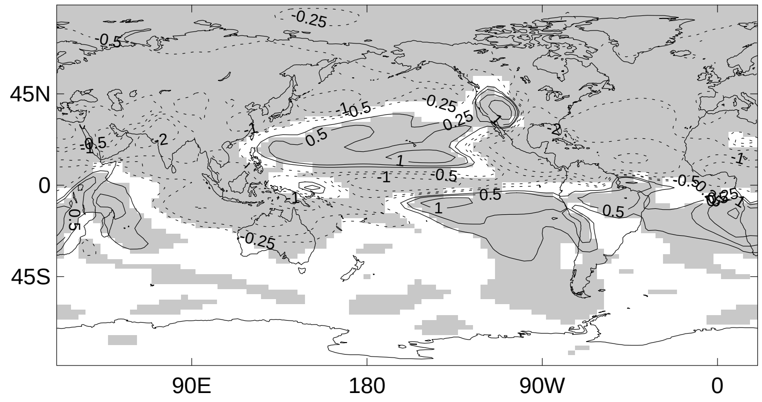


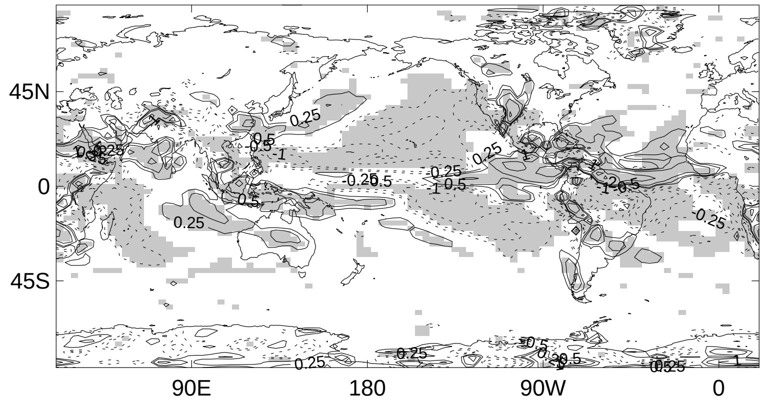
Fig. 4. The climatological mean specific humidity anomalies (g kg^{-1}) in JJA between the 1 Sv and control experiments. (a) at 1000 hPa and (b) at 850 hPa. Shading indicates regions where anomalies are significant above 95% confidence level using *t*-test.

cal eastern North Pacific in the lower troposphere (Fig. 3a), associated with the above-mentioned anticyclonic anomaly, results in a weakening of the mean northeasterly winds. The northeasterly winds over the Northeast Pacific are associated with descent flows (Hoskins, 1996). Thus, the anomalous southwesterlies over the subtropical eastern North Pacific may be related to weakened descent flows and result in more precipitation.

Subtropical diabatic heating can force significant atmospheric circulations. Based on an aqua-planet GCM study, Kodama (1999) suggested that the diabatic heating in the subtropical convergence zone (STCZ) induces a lower-level trough along the west and poleward side of the STCZ, and an accompanying upper-level trough on the west/poleward side and a ridge on the east/equatorward side of the STCZ, respectively. The lower-level eastward and poleward wind along the STCZ is intensified by the lower-level trough and this, in turn, maintains the strong convergence in the STCZ, together with the enhanced poleward moisture flow from the tropics. The lower and upper tropospheric circulation anomalies in the tropical Pacific shown in Fig. 3 bear a similarity to the results of Kodama (1999). There is a cyclonic anomaly in the subtropical North Pacific in the lower troposphere. In the upper troposphere, a cyclonic anomaly appears northward and an anticyclonic anomaly appears southward to the enhanced precipitation in the subtropical North Pacific, respectively (Fig. 1b and Fig. 3). Therefore, in the water-hosing experiment, the diabatic heating associated with the enhanced precipitations over the subtropical North Pacific result in a lower-level anomalous cyclone to the west and north, which in turn, produces a positive feedback on the enhanced precipitations by strengthening the anomalous southwesterly winds.

It should be noted that the subtropical precipitation anomaly in the present results, with a maximum magnitude of about 1 mm d^{-1}, is much weaker than the precipitation in the STCZ in Kodama (1999). However, the good agreement in the patterns of circula-

(a) 850 hPa divergence anomalies



(b) 850 hPa moisture transport divergence anomalies

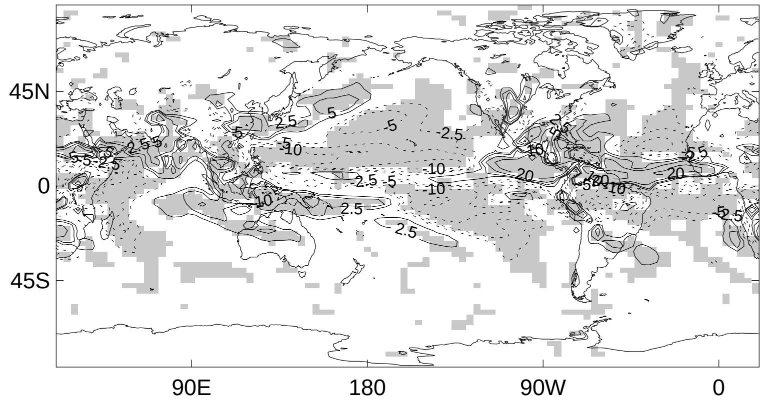


Fig. 5. The climatological mean anomalies in JJA between the 1 Sv and control experiments. (a) divergence (10^{-6} s^{-1}) at 850 hPa and (b) moisture transport divergence (10^{-6} g kg^{-1} s^{-1}) at 850 hPa. Shading indicates regions where anomalies are significant above 95% confidence level using *t*-test.

tion anomalies between the present results and Kodama's suggest that his proposed mechanism is valid for the relationship between the precipitation and circulation anomalies in the extratropical North Pacific in the water-hosing experiment.

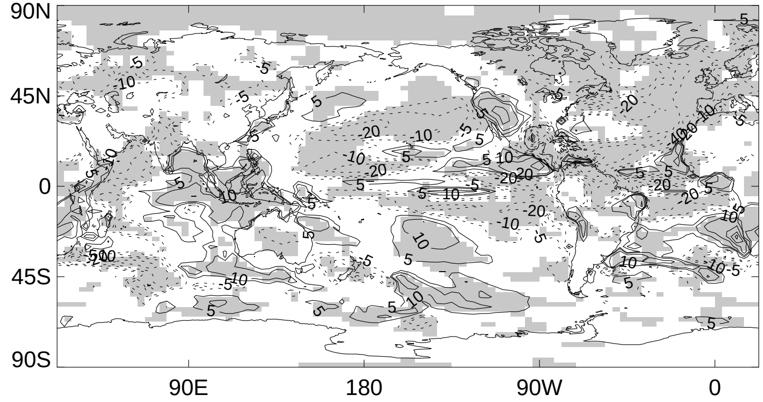
The subtropical positive precipitation anomaly, which is likely induced by the anticyclonic anomaly in the eastern North Pacific and intensified by the cyclonic anomaly in the North Pacific, may be further intensified by the enhanced precipitations in the tropical North Pacific associated with positive SST anomalies there. Kodama (1999) suggested that a zonally located off-equatorial heat source plays two roles in affecting the STCZ: one is to maintain a strong subtropical upper-level jet, and the other is to form a low-level poleward moisture flow toward the subtropics. Actually, there are strongly enhanced precipitations in the tropical North Pacific (Fig. 1b), and the circulation anomalies simulated in this study also show a strengthened subtropical upper-level jet and low-level southwesterly anomalies along the enhanced precipitation in the subtropical North Pacific (Fig. 3). Thus, the enhanced precipitation in the tropical North Pacific may facilitate the positive precipitation anomaly in the subtropics.

4.2 *Atmosphere-ocean interaction in the tropical Pacific and Indian Ocean*

Atmosphere-ocean interactions in the Pacific and Indian Ocean play an important role in Asian climate (e.g., Wang et al., 2003; Tarrey et al., 2005; Wu and Kirtman, 2005). These interactions may play a crucial role in influencing the Pacific anomalies, which are as strong as the local responses in the Atlantic.

Wind at 850 hPa (Fig. 3a) shows that the lower tropospheric westerly anomaly, associated with the North Pacific cyclonic anomaly, weakens the mean easterly trades. The weakened easterly trades result in a reduction of evaporation, and therefore, a reduction of latent heat release from the ocean into the at-

(a) upward latent heat flux anomalies



(b) surface total heat flux anomalies

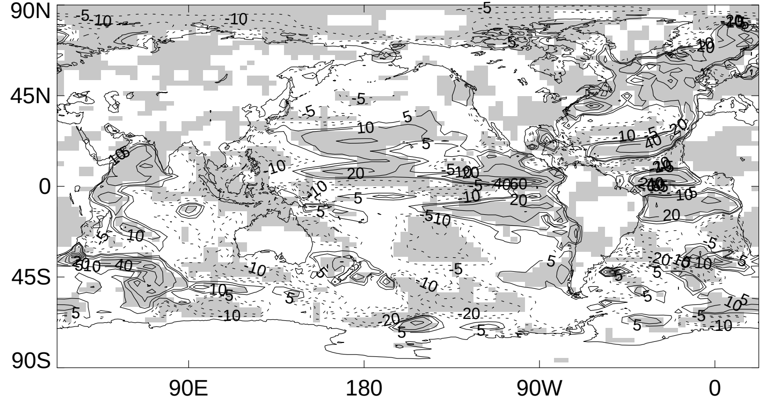


Fig. 6. The climatological mean surface heat flux anomalies (W m^{-2}) in JJA between the 1 Sv and control experiments. (a) upward latent heat flux and (b) total downward heat flux. Shading indicates regions where anomalies are significant above 95% confidence level using *t*-test.

mosphere (Fig. 6a). The anomalous latent heat flux plays a dominant role in surface heat flux anomaly (Fig. 6b), and results in warming in the tropical central North Pacific (Fig. 1a).

The cooling in the tropical western Pacific and eastern Indian Ocean is a result of coupled atmosphere-ocean feedback. As Fig. 3a indicates, the trade winds are weakened in the central and western tropical Pacific. The dynamical response to the weakened trade winds is that the thermocline in the western tropical Pacific is shoaled (by 2–5 meters), which is associated with a cooling of $\sim 0.8°\mathrm{C}$ around the depth of the mean thermocline (Dong and Sutton, 2007). This subsurface cooling could lead to surface cooling by oceanic vertical mixing. In addition, the enhanced upward latent heat flux in these regions (Fig. 6a) further amplifies the cooling. This enhanced latent heat flux from the ocean to the atmosphere, however, is associated with the dry air in these regions (Fig. 4a), rather than the change in wind speed. The negative anomaly of specific humidity is in turn favored by negative SST anomalies. Again, in these regions, anomalous latent heat flux plays a dominant role in the surface heat flux anomaly (Fig. 6b), although reduced solar radiation (not shown) due to enhanced convection plays an appreciable role in cooling the SSTs in the Philippine Sea.

The warm tropical central North Pacific and cold western Pacific/eastern Indian Ocean SSTs favor enhanced precipitation in the east and reduced precipitation in the west. This change in precipitation, in turn, leads to reduced easterly trades, and intensifies the seesaw pattern of SST anomalies. Therefore, the relationship between the precipitation, surface wind, and SST changes in these regions indicates that they are coupled responses.

The enhanced precipitation in the South China Sea and the Philippine Sea induces the lower-tropospheric cyclonic anomaly over the subtropical western North Pacific (Lu, 2001; Lu and Dong, 2001), which can be demonstrated by the baroclinic structure of circulation anomalies (Fig. 3). This subtropical cyclonic anomaly significantly reduces the precipitations in East Asia and the subtropical western North Pacific (Fig. 1b), through weakening the East Asian summer monsoon circulations.

The SST anomalies in the Indian Ocean may also facilitate the circulation and precipitation anomalies in the western North Pacific. Cold SST anomalies in the northern Indian Ocean and eastern Indian Ocean (Fig. 1a) tend to induce enhanced precipitation and a lower tropospheric cyclonic circulation anomaly in the tropical western North Pacific (Watanabe and Jin, 2002; Terao and Kubota, 2005; Yang et al., 2007). Yang et al. (2007) reproduced suppressed precipitation and a lower tropospheric anticyclonic anomaly over the tropical western North Pacific in a coupled model simulation initialized with a warming in the tropical Indian Ocean. Terao and Kubota (2005), and Watanabe and Jin (2002) proposed the possible mechanisms responsible for the effect of the Indian Ocean forcing on the circulation over the western North Pacific.

4.3 *Comparison with previous studies*

The present results are in good agreement with the JJA (June-July-August) result in Zhang and Delworth (2005). Using GFDL's coupled atmosphere-ocean model, they simulated the response to a sustained addition of freshwater to the North Atlantic, and showed that a weakened Atlantic THC leads to weakened Indian and East Asian summer monsoons (their Fig. 2f, only one figure for their summer results). In the Indian Ocean, Asian monsoon region and the western Pacific, where are the domains where Zhang and Delworth (2005) showed their summer results, the responses of precipitation and lower-tropospheric winds are considerably similar between these two experiments. This implies that the weakened Asian summer monsoon is a robust feature of the coupled ocean-atmosphere response to the weakened THC resulting from anomalous external freshwater flux in the North Atlantic.

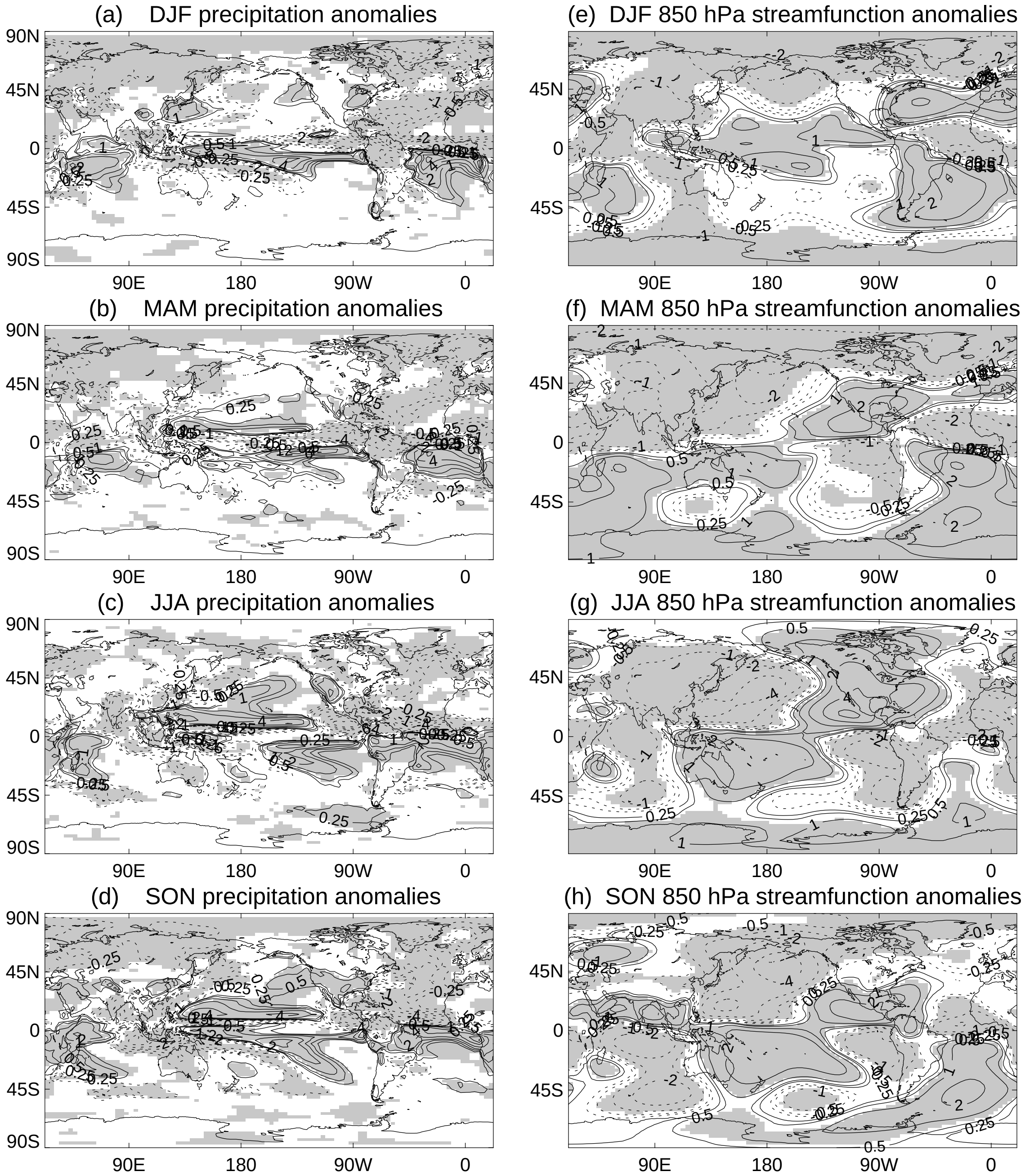
The spatial pattern of Atlantic SST anomalies in the water-hosing experiment is similar to that associated with the negative phase of AMO (Lu et al., 2006; Sutton and Hodson, 2007). Thus, comparison of the present results with previous results on the AMO's effects may provide useful insights into the mechanisms for the Atlantic Ocean forcing. Lu et al. (2006) investigated the impact of the AMO on the Asian summer monsoon by imposing the AMO-associated SST anomalies in the Atlantic in the coupled atmosphere-ocean model, which is the same as in this study. Sutton and Hodson (2007) also investigated the AMO's impacts, using the atmospheric component of HadCM3. The circulation and precipitation anomalies in the Atlantic and Pacific in the present water-hosing experiment are essentially similar (allowing for a sign change) to those forced by the AMO SST anomalies, but with much greater amplitudes. For instance, the warm phase of AMO, which shows opposite signs with the Atlantic SST anomalies in this study, induce a lower-tropospheric cyclonic anomaly over the eastern North Pacific and an anticyclonic anomaly over the extratropical North Pacific, both in the coupled model and in the atmosphere-only model (Lu et al., 2006; Sutton and Hodson, 2007). The similarity in the circulation responses in the eastern North Pacific and extratropical North Pacific between the coupled and uncoupled models suggests that the Atlantic Ocean forcing induces these circulation anomalies mainly through the atmosphere.

The precipitation anomalies in the western Pacific and Indian Ocean in the coupled model (the present study, and Lu et al. (2006)), however, differ considerably with the simulated results from the atmosphere-only model (Sutton and Hodson, 2007). For instance, the precipitation anomalies over South Asia, East Asia and the eastern Indian Ocean appear significantly in the coupled model, but not in the AGCM. The difference in results between the coupled and uncoupled experiments suggests that coupled atmosphere-ocean feedbacks play an important role in these regions, which is consistent with the discussion in the preceding subsection.

Dykoski et al. (2005) indicated that the record in Dongge Cave bears a remarkable resemblance with that in the Cariaco Basin (Haug et al., 2001) throughout the Holocene (see also Gupta et al., 2003; Fleitmann et al., 2003). Variations are of decadal to centennial scales in both records, and features are similar even in details. Data from the Cariaco Basin (10°N, 65°W), which is located at the northern edge of the annual latitudinal range of the Atlantic ITCZ, can be used to illustrate shifts in the mean latitude of the Atlantic ITCZ (Haug et al., 2001). The present results indicate that a southward shifted Atlantic ITCZ corresponds to a weakened Asian summer monsoon, and thus confirm the paleoclimate link recorded between the Dongge Cave and the Cariaco Basin.

4.4 *Seasonality*

The responses of the Atlantic Ocean forcing exhibit a clear seasonality. Figure 7 shows that the precipitation anomalies in the tropical North Atlantic are largest in JJA and SON (September-October-November), due to the seasonal cycle of basic state of SSTs in the region. This seasonality is also evident in streamfunction anomalies which show large anomalies in the Pacific in JJA and SON (right panels of Fig. 7).



(a) DJF precipitation anomalies

(e) DJF 850 hPa streamfunction anomalies

(b) MAM precipitation anomalies

(f) MAM 850 hPa streamfunction anomalies

(c) JJA precipitation anomalies

(g) JJA 850 hPa streamfunction anomalies

(d) SON precipitation anomalies

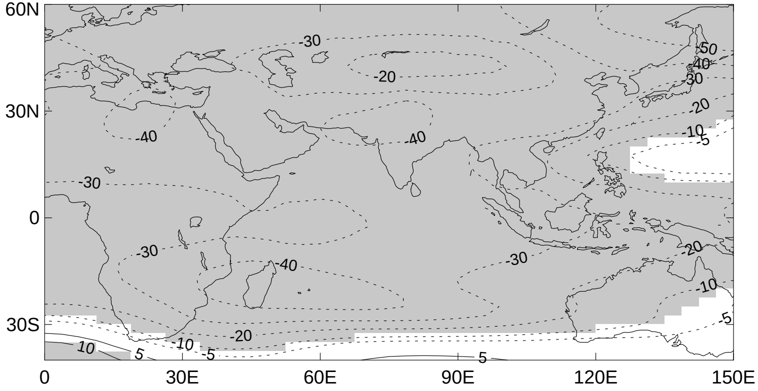
(h) SON 850 hPa streamfunction anomalies

Fig. 7. The climatological mean anomalies in four seasons between the 1 Sv and control experiments. (left) precipitation (mm d^{-1}) and (right) streamfunction (10^6 m^2 s^{-1}) at 850 hPa. Shading indicates regions where anomalies are significant above 95% confidence level using *t*-test.

This seasonal cycle of the Pacific response is in agreement with the magnitude of north tropical Atlantic precipitation anomalies. The seasonality shown in this study is consistent with Sutton and Hodson (2007), who found that the strongest remote impacts of the AMO occur in the tropical Pacific in JJA and SON. The response in the tropical Pacific is dominated by anomalous heating to the north of the equatorial Atlantic since the westward propagation of the atmospheric Rossby waves excited by diabatic heating in the south of equatorial Atlantic may be blocked by the Andes. Therefore, the magnitude of diabatic heating over the Caribbean Sea and north of the equatorial Atlantic predominantly determines the magnitude of the tropical Pacific response.

A very recent paleoclimate study (Yancheva, 2007)

(a) JJA Z200-Z500 height anomalies



(b) SON Z200-Z500 height anomalies

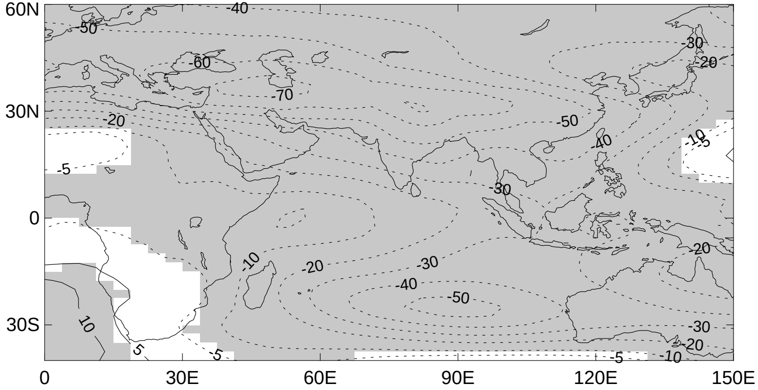


Fig. 8. The climatological mean anomalies of height difference (gpm) between 200 hPa and 500 hPa between the 1 Sv and control experiments. (a) JJA and (b) SON. Shading indicates regions where anomalies are significant above 95% confidence level using t-test.

showed an inverse correlation between the strengths of the East Asian winter and summer monsoons. Yancheva (2007) suggested that this anticorrelation can be explained by migrations in the ITCZ. The present result indicates a southward shift of the ITCZ in the Atlantic and Pacific, but not in the tropical Americas, in winter (Fig. 7a). In addition, the change in winter monsoon shown by the present results is complicated: stronger wind over northeastern Asia but weaker wind over Southeast Asia (reflected by Fig. 7e).

Goswami et al. (2006) suggested by observations that the warm AMO enhances the Indian monsoon rainfall by setting up a positive tropospheric temperature anomaly in late summer/autumn and the resulting delayed withdrawal of monsoon. This link between the AMO and Indian summer monsoon was further investigated using a hybrid coupled model by Zhang and Delworth (2006). Lu et al. (2006) found that the warm AMO induces enhanced SON precipitation in South Asia in a coupled model through the mechanism proposed by Goswami et al. (2006). The present results indicate that the Atlantic Ocean forcing induced by anomalous external freshwater flux leads to negative precipitation anomalies in India in SON (Figs. 2 and 7d), which have an amplitude (1.0–2.0 mm d^{-1}) similar to the JJA negative anomalies. In general, the SON precipitation anomalies are similar to those in JJA, but they turn to be positive in central China and on the Korean Peninsula with the amplitude of 0.2–0.5 mm d^{-1}. Figure 8 indicates that in SON, there is a much stronger negative anomaly of tropospheric temperature over southern Eurasia, relative to the tropical Indian Ocean. This spatial structure of tropospheric temperature anomalies likely results from cold surface temperature over the Eurasian continent relative to the tropical Indian Ocean in SON (not shown). The spatial pattern of Fig. 8 reduces the meridional gradient of tropospheric temperature, which is defined as the difference between a north box (10°–35°N, 30°–100°E) and a south box (15°S–10°N, 30°–100°E) by Goswami et al. (2006), and therefore leads to an earlier withdrawal of the Indian summer monsoon. These results suggest that like the AMO, the Atlantic Ocean

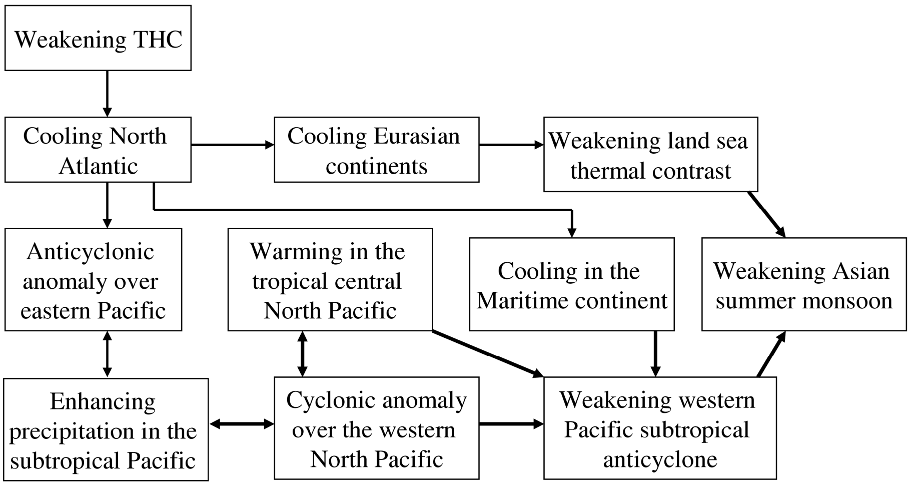


Fig. 9. A schematic illustration of the major processes involved in the influence of weakened THC on the Asian summer monsoon.

forcing induced by the weakened THC affects the Indian rainfall through the mechanism proposed by Goswami et al. (2006). Actually, both precipitation and tropospheric temperature anomalies in the present study are, in spatial distribution, similar to those induced by a warm AMO (Lu et al., 2006), with opposite signs and much stronger intensity.

Besides the reduction of the meridional gradient of tropospheric temperature, changes in the Walker circulation induced by the weakened THC (Zhang and Delworth, 2005) may also play a role in the weakening of the Indian monsoon in SON. Figure 7h, as well as the pressure-longitude cross-section of zonal wind anomalies averaged over 5°S–5°N (not shown), shows that the Walker circulation over the Pacific and Indian Ocean is reduced by the weakened THC.

5. Summary

A coupled atmosphere-ocean model, HadCM3, is utilized to simulate the Asian summer monsoon responses to the weakening of the Atlantic THC due to anomalous external freshwater forcing in the North Atlantic in an attempt to illustrate links between the suborbital variations of Asian summer monsoon and the North Atlantic Ocean that has been documented by various paleoclimate studies (e.g., Wang et al., 2001a; Gupta et al., 2003; Zhao et al., 2003; Dykoski et al., 2005). This study suggests a non-local mechanism for the Asian summer monsoon variability. The simulated results indicate that the cold North Atlantic and warm South Atlantic induced by the weakened THC lead to significantly suppressed Asian summer monsoon, which is consistent with the previously documented paleoclimate evidence.

This study then makes efforts to illustrate the processes of the Asian summer monsoon responses to the Atlantic Ocean forcing. We find that the atmospheric teleconnection in the North Pacific and the atmosphere-ocean interaction in the eastern Indian ocean and tropical North Pacific play the most important roles. A schematic illustration of the major processes involved in influencing the effect of THC on the Asian summer monsoon is given in Fig. 9. The major elements of the processes are as follows. The cold North Atlantic and warm South Atlantic under the influence of a substantially weakened THC lead to the weakening and southward shift of the Atlantic ITCZ. This heating anomaly excites a lower-tropospheric anticyclonic anomaly in the eastern Pacific, as a Gill-type response. The southwesterly anomaly associated with this anticyclonic anomaly weakens the mean northeasterlies and thus enhances precipitation in the subtropical central North Pacific. The enhanced subtropical precipitation may induce a cyclonic anomaly in the central and western North Pacific. The anomalous westerly, associated with the North Pacific cyclonic anomaly, weakens the mean easterly trades and leads to a warming in the tropical North Pacific. On the other hand, the weakened easterly trades in the tropical central and western Pacific lead to a thermocline shoaling and cold subsurface temperature anomalies around the mean thermocline in the tropical western Pacific. This leads to surface cooling through oceanic vertical mixing. In addition, the enhanced latent heat flux from ocean to atmosphere due to drier air further amplifies this cooling. The cold SST anomalies in the tropical western Pacific and eastern Indian Ocean, together with the warm SST anomalies in the tropical central North Pacific, further weakens the mean easterly trades in the tropical central and western Pacific. The enhanced precipitation in the tropical North Pacific strengthens the cyclonic anomaly over the subtropical western North Pacific as a Gill-type response, and the East Asian summer monsoon is significantly weakened due to the cyclonic anomaly. In addition, this enhanced tropical precipitation may further intensify the subtropical positive anomaly in the North Pacific (Kodama, 1999).

Furthermore, the Atlantic Ocean forcing induced by anomalous external freshwater flux suppresses the Indian rainfall in autumn through the weakening of the meridional gradient of tropospheric temperature (Goswami et al., 2006) and reduced Walker circulation. The responses to the Atlantic Ocean forcing exhibit a clear seasonality: strongest in JJA and SON.

Although this study shows the processes of the Atlantic impact on the Asian summer monsoon, the detailed mechanisms proposed for these processes need to be elucidated with specially designed experiments. An important question that remains to be answered is: what is the relative role of coupled feedbacks in the tropical Pacific and Indian ocean and the relative role of land surface conditions over the Eurasian continent?

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