ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 33, FEBRUARY 2016, 151–163

Influence of Soil Moisture in Eastern China on the East Asian Summer Monsoon

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(Received 6 May 2015; revised 23 July 2015; accepted 27 August 2015)

ABSTRACT

The sensitivity of the East Asian summer monsoon to soil moisture anomalies over China was investigated based on ensembles of seasonal simulations (March–September) using the NCEP GCM coupled with the Simplified Simple Biosphere Model (NCEP GCM/SSiB). After a control experiment with free-running soil moisture, two ensembles were performed in which the soil moisture over the vast region from the lower and middle reaches of the Yangtze River valley to North China (YRNC) was double and half that in the control, with the maximum less than the field capacity. The simulation results showed significant sensitivity of the East Asian summer monsoon to wet soil in YRNC. The wetter soil was associated with increased surface latent heat flux and reduced surface sensible heat flux. In turn, these changes resulted in a wetter and colder local land surface and reduced land–sea temperature gradients, corresponding to a weakened East Asian monsoon circulation in an anomalous anticyclone over southeastern China, and a strengthened East Asian trough southward over Northeast China. Consequently, less precipitation appeared over southeastern China and North China and more rainfall over Northeast China. The weakened monsoon circulation and strengthened East Asian trough was accompanied by the convergence of abnormal northerly and southerly flow over the Yangtze River valley, resulting in more rainfall in this region. In the drier soil experiments, less precipitation appeared over YRNC. The East Asian monsoon circulation seems to show little sensitivity to dry soil anomalies in NCEP GCM/SSiB.

Key words: soil moisture, East Asian summer monsoon, eastern China

Citation: Zuo, Z. Y., and R. H. Zhang, 2016: Influence of soil moisture in eastern China on the East Asian summer monsoon. *Adv. Atmos. Sci.*, **33**(2), 151–163, doi: 10.1007/s00376-015-5024-8.

1. Introduction

As an important component of surface hydrology, soil moisture plays a major role in the surface energy budget and thus strongly influences the atmosphere over a range of temporal and spatial scales (e.g., Dickinson and Henderson-Sellers, 1988; Mahfouf, 1991; Dirmeyer and Shukla, 1993; Ma et al., 2000; Douville, 2002; Thiaw and Mo, 2005; Kanae et al., 2006). The nature of soil moisture–precipitation feedback shows regional variations (Yeh et al., 1984; Schär et al., 1999; Collini et al., 2008; Alfieri et al., 2008; Wu and Kinter III, 2009; Vivoni et al., 2009; Dirmeyer, 2011; Hirschi et al., 2011). The impact of soil moisture on precipitation over continental interiors is generally simple: the water added to the land surface during a precipitation event corresponds to increased evaporation, in turn resulting in further rainfall. However, for regions in which precipitation is determined by monsoonal circulation, the impact of soil moisture is complicated due to the contrasting effects of soil moisture conditions on monsoonal circulation via changes in surface temperature and the supply of water vapor to the overlying air column (Meehl, 1994; Douville et al., 2001). A greater understanding of the influence of soil moisture on the atmosphere should lead to improved forecasts of soil moisture itself, as well as other fields such as precipitation, temperature, and evaporation (e.g., Yang et al., 1994; Zampieri et al., 2009; Li et al., 2015).

The region of eastern China is well known for soil moisture anomalies having a significant influence on atmospheric circulation and precipitation (Koster et al., 2004; Kim and Hong, 2007). For instance, our group's previous studies, based on observation analysis (Zuo and Zhang, 2007; Zhang and Zuo, 2011), reported that the East Asian summer monsoon and rainfall in China show a significant correlation with springtime soil moisture over the vast region from the lower and middle reaches of the Yangtze River valley to North China (YRNC). Weaker East Asian summer monsoon circulation is associated with greater springtime soil moisture over YRNC, resulting in above-normal rainfall in Northeast China and the Yangtze River valley, and below-normal rainfall in southern China and North China. Using the U.S. Climate Prediction Center soil moisture dataset, Zhan and Lin (2011) reported that the spring wet soil anomalies over the East Asian monsoon region correspond to a cold tropospheric atmosphere in May, and thereby conducive to a weaker East Asian monsoon, consistent with the conclusion of Zuo and Zhang (2007) and Zhang and Zuo (2011). However, based

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on data from the 40-yr European Centre for Medium-Range Weather Forecasts Reanalysis, Meng et al. (2014) argued that the significant relationship between spring soil moisture and summer rainfall, as suggested by Zuo and Zhang (2007) and Zhang and Zuo (2011), might be the consequence of the combination of soil moisture–precipitation interactions and precipitation autocorrelation. The lack of consensus may be the consequence of the different datasets used; over eastern China, observational soil moisture data exhibit large discrepancies with reanalysis data (Zuo and Zhang, 2009; Liu et al., 2014). Therefore, it is necessary to further document the relationship between spring soil moisture over eastern China and the East Asian summer monsoon system using numerical models. Previous modeling studies have reported a significant relationship between initial spring soil moisture anomalies and Asian summer monsoon circulation over East Asia (e.g., You et al., 2000; Kim and Hong, 2007), but these studies used idealized soil moisture sensitively experiments. Thus, further investigation with more realistic soil moisture anomalies is required. The ultimate aim of the present study was to verify the observational analyses of Zuo and Zhang (2007) and Zhang and Zuo (2011) with numerical model results. Specifically, the influence of spring soil moisture over eastern China on the East Asian summer monsoon system, and summer precipitation, was investigated using a numerical model with realistic soil moisture anomalies.

Since the National Center for Environmental Prediction (NCEP) GCM coupled with the Simplified Simple Biosphere Model (SSiB) improves the simulation of the structure and characteristics of the Asian summer monsoon system (Xue et al., 2004), it was used in the present study to verify the observed significant relationship between spring soil moisture and summer rainfall over eastern China, and further investigate the relevant physical processes. The remainder of this paper is organized as follows: NCEP GCM and the SSiB land surface scheme are briefly described in section 2, along with the design of the seasonal climate simulations. Section 3 discusses the main features of the climate in the control (CTRL) experiment, and section 4 analyzes the sensitivity of the monsoon circulation and rainfall to soil moisture anomalies. Section 5 further discusses the plausible causes for the different responses of the East Asian summer monsoon to abnormally wet or dry soil, and the impact of SST anomalies on soil moisture–precipitation feedback. Finally, a summary of the results and the main conclusions are provided in section 6.

2. Data and methods

The NCEP GCM, with 28 levels and T62 horizontal resolution (Kalnay et al., 1990; Kanamitsu et al., 1991), was used for a range of model runs. The SSiB biosphere model (Xue et al., 1991, 1996, 2004; Hansen et al., 2000) is a simplified version of the Simple Biosphere Model (SiB) (Seller et al., 1986), and was coupled with NCEP GCM in this study. In describing the surface water balance, SSiB includes processes such as water interception loss, direct evaporation from bare soil, and canopy transpiration. The storage of canopy-intercepted water is based on water conservation. In the three soil layers, water movement is described by a finite-difference approximation to the diffusion equations

$$\begin{aligned}\frac{\partial\theta_1}{\partial t} &= \frac{1}{D_1}(P+Q_{12}-E_{\rm gs}-b_1E_{\rm dc})\ ,\\ \frac{\partial\theta_2}{\partial t} &= \frac{1}{D_2}(-Q_{12}+Q_{23}-b_2E_{\rm dc})\ ,\\ \frac{\partial\theta_3}{\partial t} &= \frac{1}{D_3}(-Q_{23}-Q_3-b_3E_{\rm dc})\ ,\end{aligned}$$

where $\theta_1, \theta_2, \theta_3, D_1, D_2$ and D_3 are the volumetric soil water content and soil thickness of the top (0–10 cm from the ground surface), middle (0–44 cm), and deep (10–200 cm) soil layers, respectively; $E_{\rm dc}$ is the transpiration rate; $E_{\rm gs}$ is evaporation from bare soil; b_i $(i = 1,2,3)$ is the fraction factor, which depends on the root distribution; and Q_j $(j = 1,2,3)$ is the transfer of water between the ith and jth layers. SSiB provided momentum flux, sensible and latent heat flux, radiative skin temperature, and visible and near-infrared albedo for both direct and diffuse radiation to the GCM.

Given that the present study focuses on seasonal variations, all atmospheric simulations were forced with prescribed climatological monthly mean SST, sea ice, and snow depth. The soil moisture conditions were controlled in YRNC (30°–40°N, 105°–120°E) based on the observational analysis of Zuo and Zhang (2007) and Zhang and Zuo (2011). We set a 2° intermediate zone around the controlled domain, in which the soil moisture constraint gradually diminished to zero, to ensure a smooth transition between the controlled soil moisture area and other free-running soil moisture areas (Fig. 1). In the climatology, the initial soil moisture in the top and deep soil layers over YRNC in CTRL gradually increased from south to north, with a minimum of less than 0.15 around Shandong Province and a maximum larger than 0.3 around the Yangtze River valley (Fig. 2). Generally, the soil moisture in the deep soil layer was slightly greater than

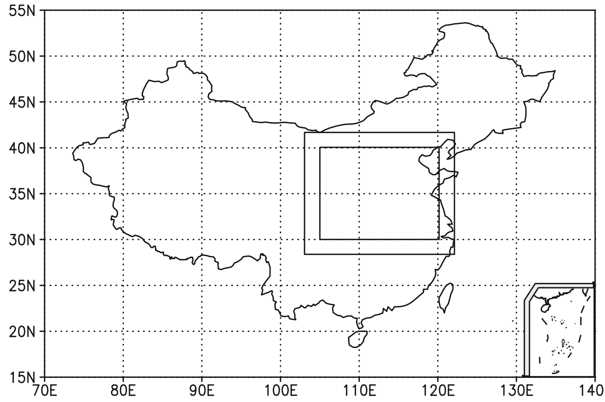

Fig. 1. Geographical domain in which soil moisture was controlled. The control was gradually diminished from the inner boundary to the outer boundary of the domain.

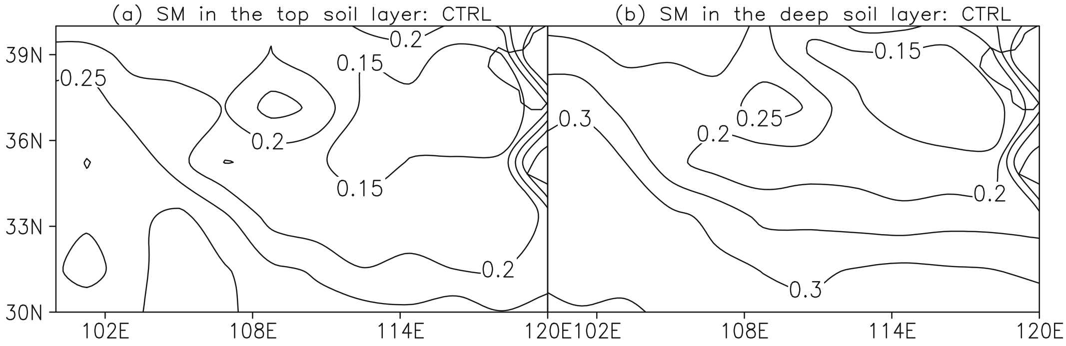

Fig. 2. Spatial distribution of soil moisture in the (a) top soil layer and (b) deep soil layer, in CTRL.

that in the top soil layer.

Because the focus of this study was the summer monsoon, all simulations ran from mid-March to the end of September. Each experiment comprised an ensemble of six seven-month integration members, using the same boundary conditions but different initial conditions, to delete the noise derived from the internal atmospheric variability. The initial conditions of 11, 13, 15, 17, 19 and 21 March 1990, derived from the NCEP/NCAR (National Center for Atmospheric Research) Global Reanalysis were applied. Since the model was initialized between 11 and 21 March, it ran for at least one month before the onset of the East Asian summer monsoon, and thereby avoided any spurious behavior related to the spin-up of the atmosphere. Additionally, 1990 was neither an El Niño year nor a La Niña year, thereby eliminating the possible impact of robust SST anomalies on the initial condition. In the analysis presented in this paper, only the significant impacts of soil moisture are discussed. The ensembles are mainly compared for May, and for June–July–August (JJA).

We ran three experiments: CTRL; a wet soil experiment (WSM); and a dry soil experiment (DSM). The only difference among the three experiments was the initial soil moisture value. CTRL was used to verify that NCEP GCM/SSiB is able to reasonably depict the main features of the Asian monsoon. A number of datasets were used to validate the CTRL results, including 200 and 850 hPa winds from the NCEP reanalysis dataset, and observed (160-station) precipitation from the China Meteorological Administration (CMA). In WSM, the initial soil moisture values in all three soil layers over YRNC were increased to double those in CTRL, with the maximum value not exceeding the field capacity. The differences between WSM and CTRL were analyzed to assess the impact of wetter spring soil over YRNC on the East Asian summer monsoon. DSM was the same as WSM but with the initial soil moisture over YRNC set to half that in CTRL. The differences between the outputs of CTRL and DSM indicated the effects of dryer springtime soil on the East Asian summer monsoon.

3. Control experiments

The sensitivity of a complex system is likely to depend on its basic state. Therefore, we needed to validate the main features of the climate before investigating the climate response to the soil moisture anomalies. Since NCEP GCM/SSiB uses T62 truncation, the validation focused on whether the main features of the East Asian summer monsoon were reasonably depicted. Figure 3 shows the climatological JJA horizontal winds at 200 hPa and 850 hPa from CTRL and NCEP reanalysis. As can be seen, NCEP GCM/SSiB performs reasonably well in simulating the upper-tropospheric atmospheric circulation (Figs. 3a and b). Both the reanalysis data and model outputs show that a large-scale anticyclonic circulation exhibits a dominant influence over southern Asia and the surrounding oceans, with the center located at (25°N, 95°E). The southern side of the anticyclone is dominated by the easterly monsoonal flow. The Asian low-level westerly jet is also captured (Figs. 3c and d). The model is successful in capturing these basic features of the East Asian monsoon circulation. However, a number of discrepancies between the reanalysis data and simulation results also exist. Specifically, the model overestimates the intensity of upper-level northeasterly flow and the low-level southwesterly jet over the equator and tropical Southern Hemisphere, and underestimates the intensity of upper-level westerly flow over the middle and high latitudes. Additionally, the model simulates easterly flow in the lower troposphere over southeastern China, which is inconsistent with the observed southerly flow.

Figure 4b shows the climatology of observed (CMA) climatological JJA rainfall from over eastern China. The minimum JJA rainfall is located over Inner Mongolia, increasing southward. The centers of maximum JJA rainfall are located over southeastern China and southwestern China, near the eastern Tibetan Plateau. CTRL performed reasonably well in capturing these main features (Fig. 4a). However, compared with observations, the model overestimates the maximum rainfall centers over southeastern and southwestern China, and underestimates the rainfall over Shandong Peninsula.

4. Influence of soil moisture anomalies on the East Asian monsoon

4.1. *Land–atmosphere energy exchange*

The variability of soil moisture has a significant impact on surface energy fluxes (Amenu et al., 2005, Zhang and

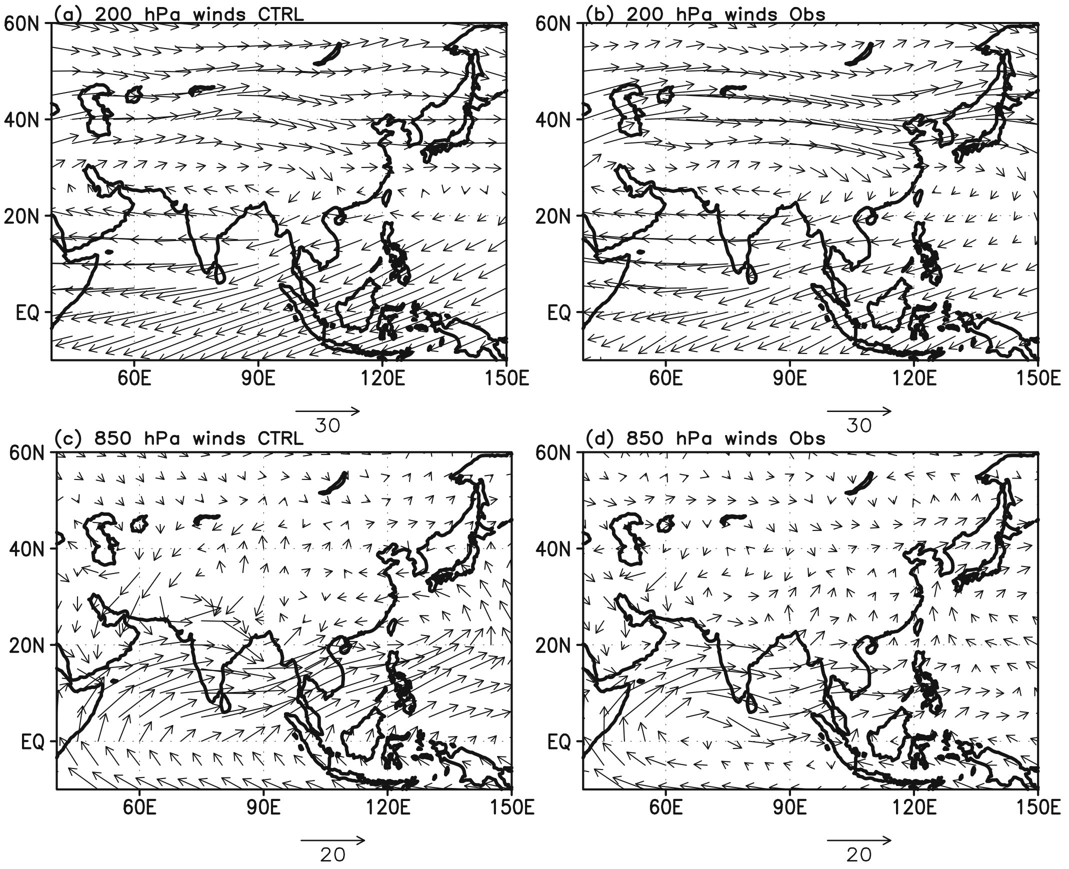

Fig. 3. JJA horizontal winds at (a) 200 hPa and (c) 850 hPa wind (units: m s^{-1}) in CTRL. (b, d) As in (a, c) but for the observation ("Obs"; NCEP reanalysis).

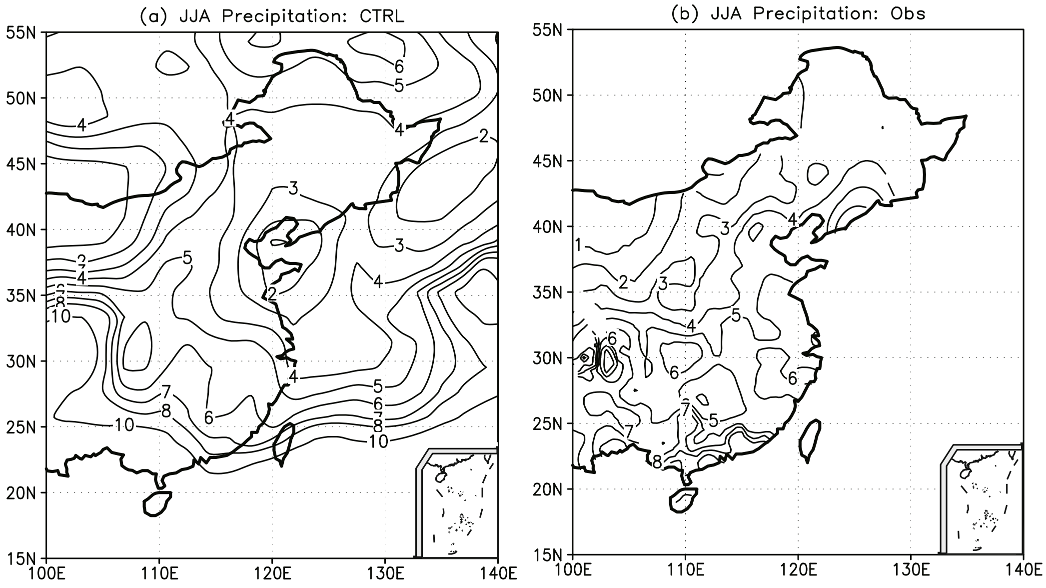

Fig. 4. JJA rainfall (units: mm d^{-1}) in (a) CTRL and (b) the observation ("Obs"; CMA).

Zuo, 2011). It first influences evaporation, and thereby affects the sensible heat flux, latent heat flux, and radiation flux exchange between the land surface and the atmosphere. Figure 5 shows the surface air specific humidity in May in WSM and DSM compared with CTRL. The positive (negative) soil moisture anomalies correspond to positive (negative) specific humidity anomalies due to the effect of evaporation. In WSM, the increasing soil moisture is associated

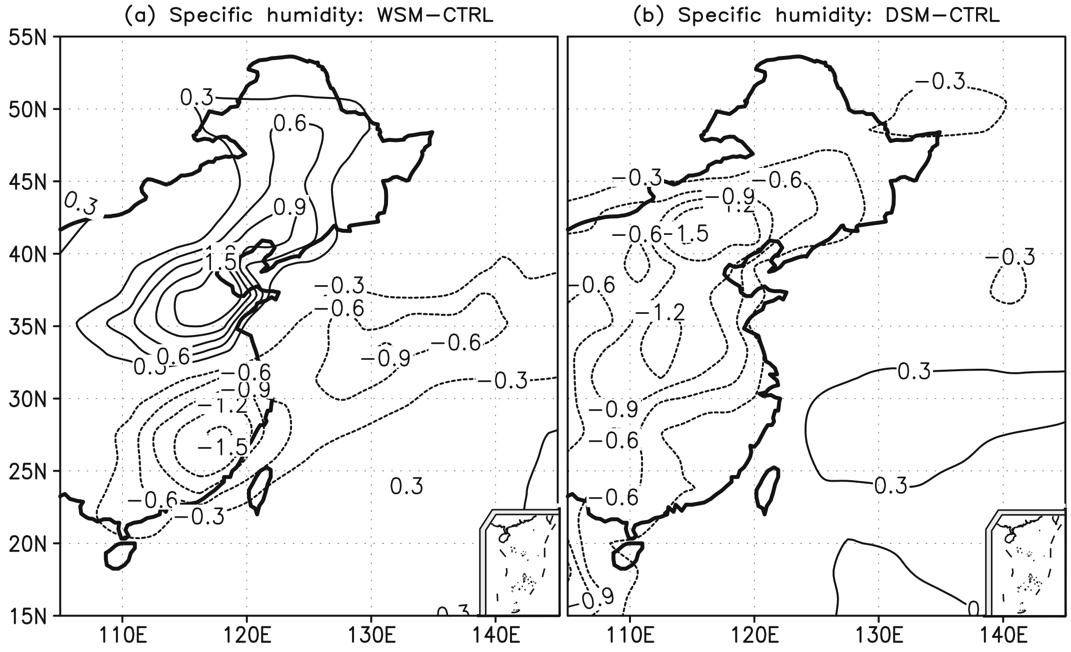

Fig. 5. Difference in surface air specific humidity (units: g kg^{-1}) in May between CTRL and (a) WSM and (b) DSM.

with enhanced specific humidity north of 30°N, with a maximum (1.5×10^{-3} g kg^{-1}) around North China (Fig. 5a). The reduced soil moisture corresponds to a reduced specific humidity over the whole of eastern China, with a maximum (-1.5×10^{-3} g kg^{-1}) around southern Northeast China (Fig. 5b).

The anomalies in humidity influence the surface energy budget. In WSM, greater latent heat flux and reduced sensible heat flux appear over most of YRNC and Northeast China, with maximum changes of 70 W m^{-2} for latent heat flux and -55 Wm^{-2} for sensible heat flux, over the area between the Huaihe River valley and the Yangtze River valley (Figs. 6a and b). Conversely, lower evaporation due to less initial soil moisture is accompanied by reduced latent heat flux and greater sensible heat flux over all of eastern China, except for a small part of Northeast China, with maximum changes of -55 W m^{-2} for latent heat flux and 40 W m^{-2} for sensible heat flux, over the Yangtze River valley (Figs. 6e and f).

In short, increased (reduced) evaporation from the land surface results from wetter (dryer) soil, which is associated with reduced (increased) sensible heat flux and increased (reduced) latent heat flux, indicating lower (higher) Bowen ratios. Low (high) Bowen ratios are generally accompanied by a cold (warm) land surface, which leads to reduced (enhanced) net long wave radiation. As expected, the maximum change (-15 W m^{-2}) in the WSM experiment occurs in the area between the Huaihe valley and the Yangtze River valley, while the maximum change (15 W m^{-2}) in the DSM experiment occurs in the Yangtze River valley (Figs. 6d and h). Generally, the net solar radiation absorbed by the soil shows a decrease (increase) in WSM (DSM), but this effect is much weaker than the change in longwave radiation (Figs. 6c and g). The change in net radiative energy flux is small compared with that in heat flux.

Figure 7 shows the influence of soil moisture on the surface air temperature anomalies in May and JJA. The center of the simulated temperature anomalies in May is located over North China in WSM (maximum of -2.5 K), and over the Yangtze River valley and southern Northeast China in DSM (maximum of 1.5 K). Specifically, although the positive (negative) soil moisture anomalies correspond to lower (higher) temperature, the surface air temperature anomalies in WSM are much larger than those in DSM before the onset of East Asian summer monsoon. Using observational data, Zhang and Zuo (2011) reported that abnormally high soil moisture over YRNC in spring is associated with a cold land surface in late spring because of the important effect of evaporation in the surface energy budget. Clearly, the simulations based on NCEP GCM/SSiB verify this observation. The positive (negative) soil moisture anomalies correspond to lower (higher) temperature, even after the onset of the East Asian summer monsoon (Figs. 7c and d), with the center of the simulated temperature anomalies situated over North China in WSM (maximum of -1.0 K) and over the Yangtze River valley in DSM (maximum of 1.5 K). Outside the domain with controlled soil moisture, there is a center of negative temperature anomalies over Northeast China in WSM, with a maximum of -1.5 K, which is greater than that over YRNC.

4.2. *East Asian summer monsoon circulation*

Given that the monsoon is the atmospheric response to a reversal in land–sea thermal contrast, the temperature anomalies associated with abnormal soil moisture probably have a strong influence on large-scale monsoonal circulation. This hypothesis is confirmed by the horizontal winds at 200 and 850 hPa (Fig. 8). The upper easterly monsoonal flow and the low-level westerly monsoonal jet in WSM are much weaker than those in CTRL over tropical Asia, the Indian Ocean, and part of the western Pacific (Figs. 8a and b). A stronger upper-level westerly jet in the middle latitudes and cyclonic circulation appear over Mongolia and adjacent areas, representing a relatively deep East Asian trough. An anomalous dipole pattern of geopotential height at 500 hPa is apparent across the Yangtze River valley, with an abnormal high to its south and an abnormal low to its north (Fig. 9a). Specifically, an abnormal high dominates southeastern China and a strengthened East Asian trough extends southward to Northeast China. These features indicate a weaker summer monsoon. An anticyclonic circulation appears over the subtropical western Pacific and southeastern China in the low-level troposphere, which inhibits rainfall in southeastern China but brings more moisture to the Yangtze River valley. The anomalous northwesterly in the low-level troposphere over midlatitude areas converges with the warm and wet southwesterly wind over the Yangtze River valley, indicating the occurrence of vapor flux convergence. As a consequence, there is more rainfall in this region. The strengthened East Asian trough extends southward to Northeast China, bringing more rainfall.

Generally, the East Asian summer monsoon circulation shows little response to dryer soil anomalies. The upper monsoon circulation shows a weak intensification over the western Pacific Ocean and the South China Sea, but diminishes in the regions to their west (Fig. 8c). The low-level horizontal winds also do not exhibit any apparent change (Fig. 8d). Additionally, moderate positive geopotential height anomalies dominate the whole of eastern China, indicating the likeli-

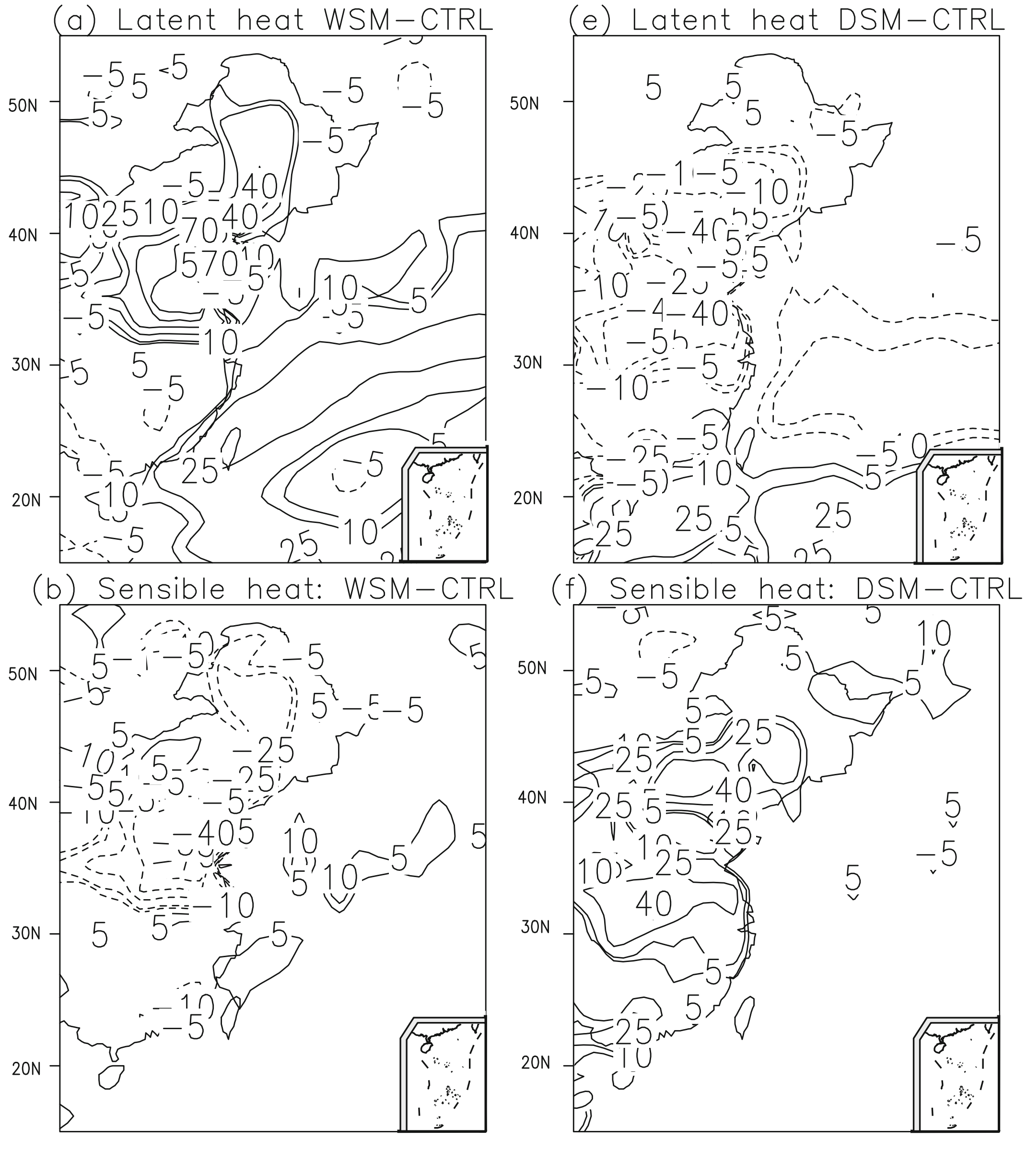

Fig. 6. Difference in (a) surface latent, (b) sensible heat flux, (c) short wave radiation, and (d) long wave radiation (units: W m^{-2}) in May between CTRL and WSM. (e–h) As in (a–d) but for the difference between CTRL and DSM.

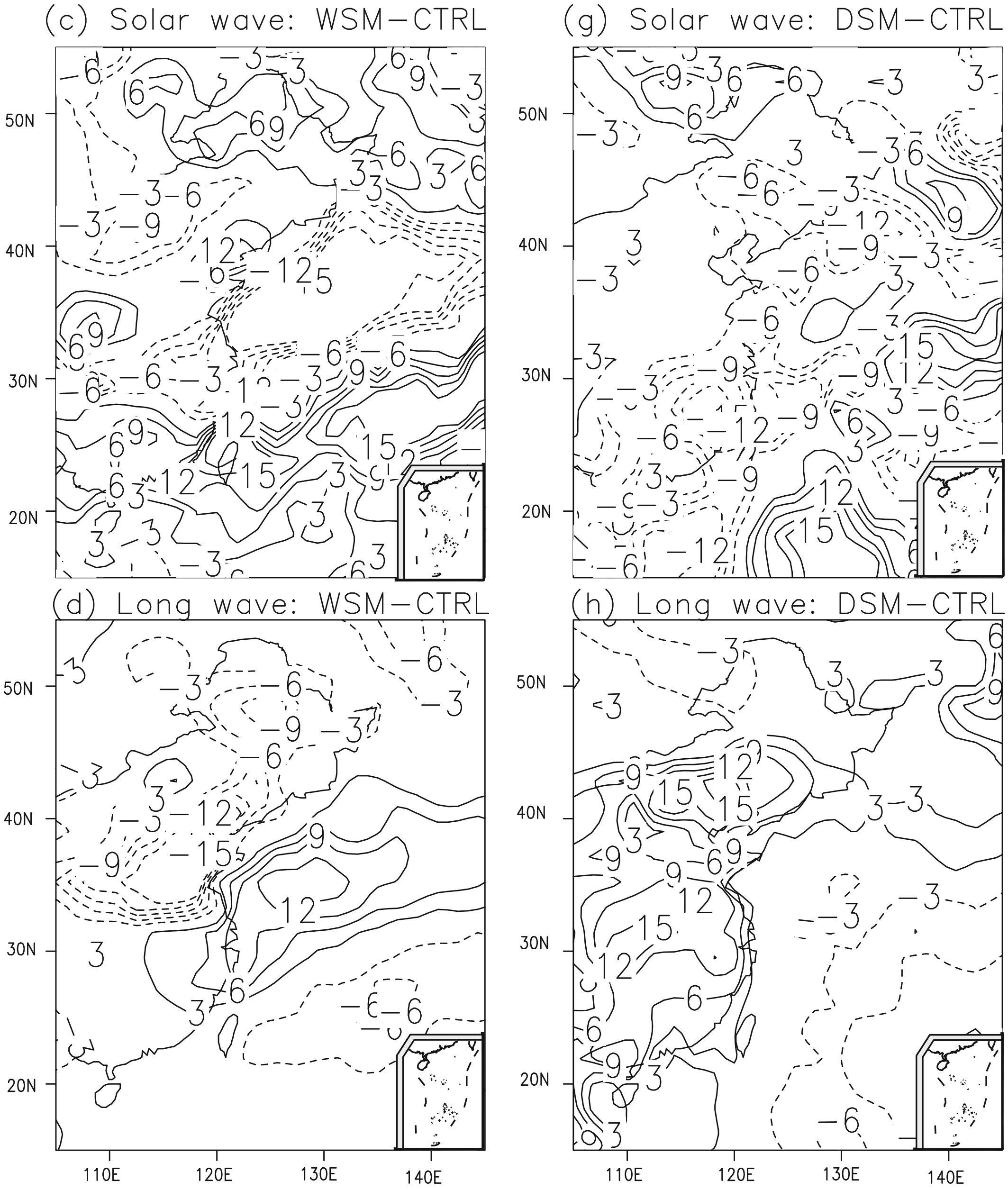

Fig. 6. (Continued.)

hood of negative rainfall anomalies over the whole of eastern China (Fig. 9b). It seems that the monsoonal circulation is insensitive to a warmer land surface over eastern China.

Figure 10 shows the latitude–height changes of JJA vertical wind along 100°–120°E in the WSM and DSM experiments compared with CTRL. In WSM, ascending motion occurs in the Yangtze River valley and Northeast China, while descending motion occurs over North China and southeastern China (Fig. 10a). Consequently, rainfall in WSM increases over the Yangtze River valley and Northeast China, but decreases in southeastern China and North China, compared with CTRL (Fig. 11a). These features are similar to those observed during years with a weak East Asian summer monsoon. Figure 11a also shows similarities with the observational findings of Zuo and Zhang (2007, Fig. 1a) and Zhang and Zuo (2011, Fig. 5), indicating consistency in the anomalous rainfall pattern between the simulated and observed results. In DSM, the positive geopotential height anomalies over the whole of eastern China correspond to the descending flow over YRNC (Fig. 10b), resulting in decreasing rainfall over the whole of YRNC (Fig. 11b).

We further calculated the net vertically integrated (1000–300 hPa) water vapor budget anomalies over southern China (20°–25°N, 105°–120°E), the Yangtze River valley (25°–35°N, 105°–120°E) and Inner Mongolia (35°–45°N, 105°–120°E) in WSM, and over YRNC in DSM, compared with CTRL. In WSM, net water vapor flux divergences are seen in southern China (-9.49×10^{-7} kg s^{-1}) and Inner Mongo-

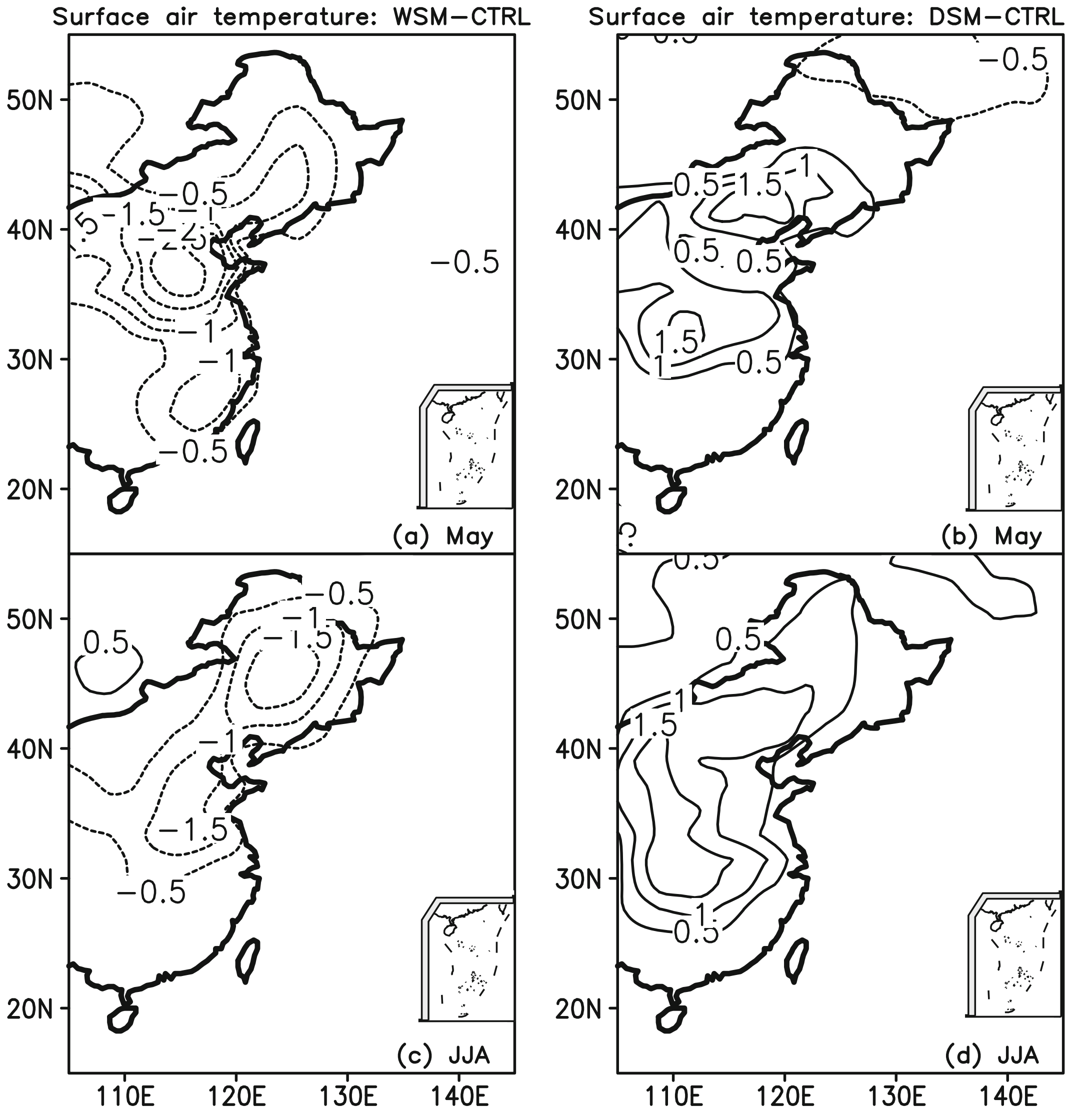

Fig. 7. Difference in 2 m air temperature (units: K) in (a) May and (b) JJA between CTRL and WSM. (c, d) As in (a, b) but for the difference between CTRL and DSM.

lia (-8.38×10^{-7} kg s^{-1}), and a net water vapor flux convergence appears in the Yangtze River valley (5.11×10^{-7} kg s^{-1}), consistent with the characteristics of rainfall anomalies. This feature verifies the weakening monsoon circulation being due to the wetter soil in spring over YRNC. In contrast, the water vapor budget anomaly over YRNC in DSM is weak (-0.72×10^{-7} kg s^{-1}), suggestive of a weak variation in the atmospheric circulation response to drier spring soil anomalies. Douville et al. (2001) suggested that soil moisture affects monsoonal precipitation via two competing processes: (1) a recycling effect, whereby greater evaporation leads to enhanced rainfall; and (2) a dynamic effect, whereby surface evaporation cools the land surface and weakens the monsoonal flow. From the present study, it appears that the dynamic effect has a more important impact on soil moisture–precipitation feedback under high spring soil moisture conditions (i.e., as shown in WSM); whereas, the recycling effect is dominant under drier conditions (i.e., as shown in DSM). East Asian summer monsoon circulation seems insensitive to dry soil anomalies.

5. Further discussion

The present study shows that wet soil results in a reduced intensity of the East Asian summer monsoon via cooling of the land surface; whereas, dry soil appears to cause little change in the monsoonal circulation. These findings are consistent with the results of Yang and Lau (1998), who reported that Asian summer monsoon becomes weaker with increased soil moisture, but does not become stronger with reduced soil moisture. Wei et al. (2008) also reported that a negative–dominant soil moisture–precipitation correlation pattern exhibits stronger negative correlations in wet areas than in dry areas.

But why is it that reduced soil moisture is not followed by a strong summer monsoon? If the persistence of soil mois-

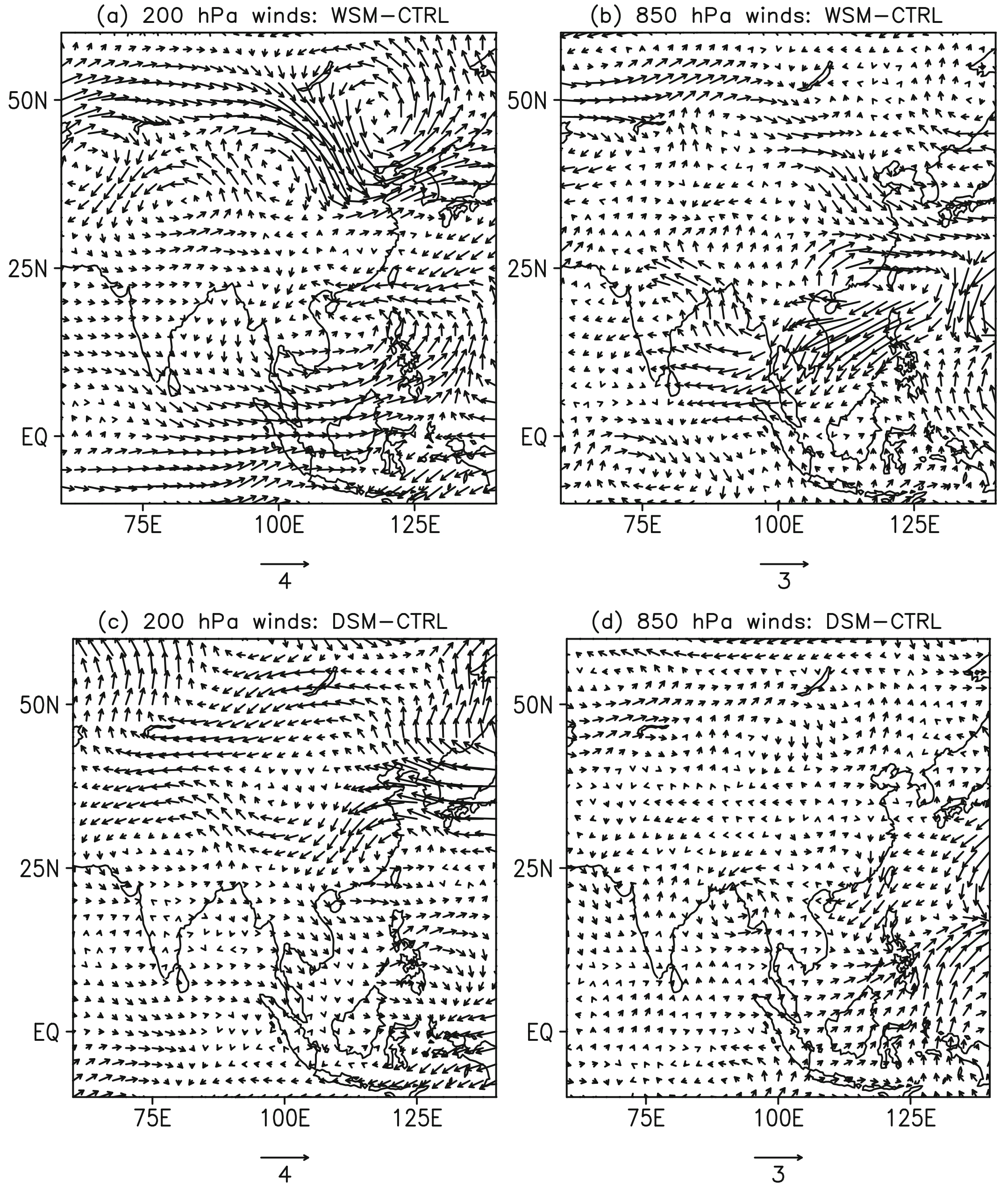

Fig. 8. Difference in JJA horizontal wind (units: m s^{-1}) at (a) 200 hPa and (b) 850 hPa between CTRL and WSM. (c, d) As in (a, b) but for the difference between CTRL and DSM.

ture in DSM was shorter than that in WSM, this may offer an explanation. However, we found that the soil moisture anomalies were larger in DSM than in WSM, in May and JJA, indicating the persistence of soil moisture anomalies was longer in DSM than in WSM (Fig. 12). Therefore, the difference in the persistence of soil moisture under dry and wet conditions cannot explain the stronger response of the Asian summer monsoon to wet soil anomalies compared with dry soil anomalies. On the other hand, the anomalous surface air temperature associated with the relatively moderate positive soil moisture in WSM in May was much larger than that associated with the relatively intense negative soil moisture in DSM (Fig. 7), which may explain the stronger response of the East Asian summer monsoon in WSM compared with that in DSM. Additionally, NCEP GCM/SSiB simulates a stronger East Asian summer monsoon circulation compared with the observation. This may be another possible cause, since a vigorous monsoon circulation is more easily weakened than strengthened via external forcing.

Additionally, Yang and Lau (1998) compared the impacts of soil moisture and SST on the Asian summer monsoon, concluding that SST anomalies cause greater change. A wetter Asian continent is associated with a moderately weaker Asian summer monsoon, considered to represent the indirect impact of SST. That is, warm winter–spring SST anomalies lead to increased soil moisture across the Asian continent and

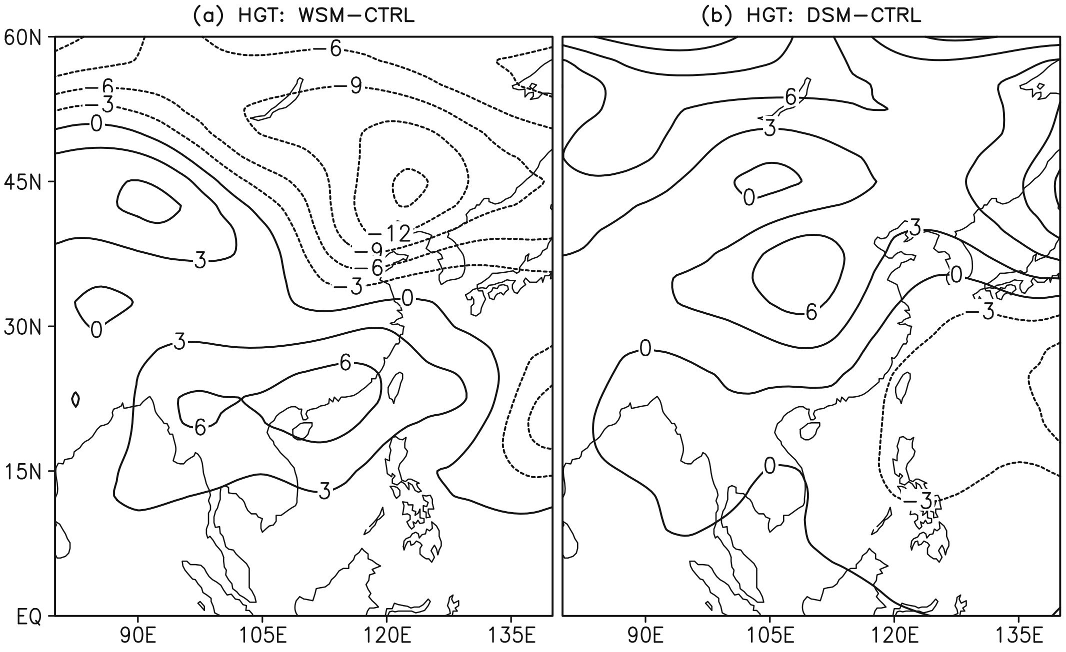

Fig. 9. Difference in JJA geopotential height at 500 hPa between CTRL and (a) WSM and (b) DSM.

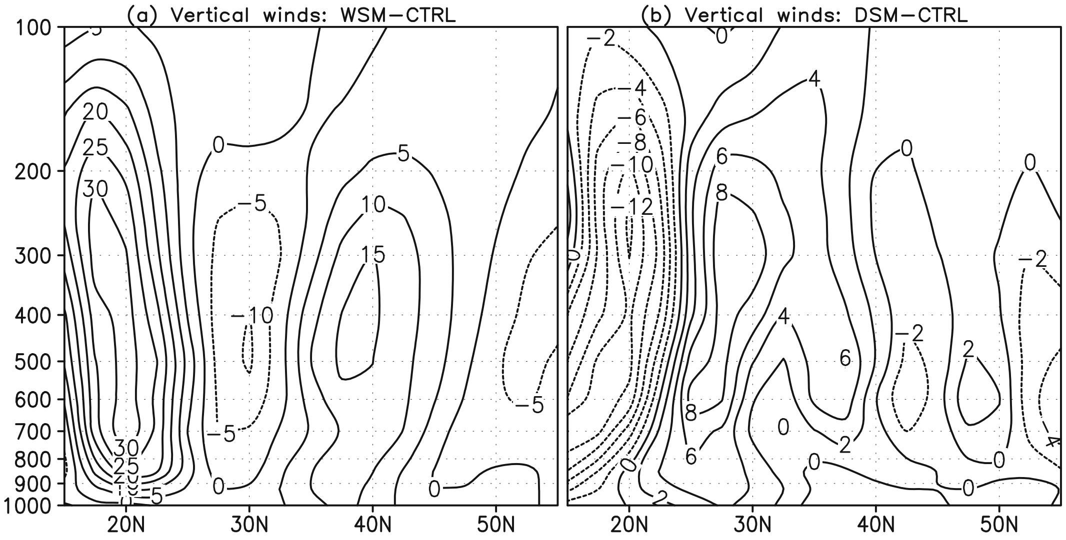

Fig. 10. As in Fig. 9 but for the latitude–height section of JJA vertical winds along 100°–120°E (units: 10^3 pa s^{-1}).

indirectly weaken the Asian monsoon during the following summer. The spring climate over eastern China is significantly affected by the SST in the central and eastern Pacific (Zhang et al., 1999, Zhang and Sumi, 2002). With this in mind, we calculated the correlation coefficients between observed soil moisture and rainfall in YRNC during spring, and wintertime SST in the Niño3 area [where Yang and Lau (1998) reported the centers of SST anomalies]. Although a significant correlation was found to exist between wintertime SST in Niño3 and springtime rainfall in YRNC ($R = 0.47$ for 1982–2010, exceeding the 0.05 level of significance), no significant relationship was found between SST and springtime soil moisture over YRNC ($R = 0.18$ for 1982–2010). Therefore, the impact of soil moisture anomalies over eastern China on the East Asian summer monsoon is independent of the SST over the tropical Pacific.

6. Summary and conclusion

Based on observed data, Zuo and Zhang (2007) and Zhang and Zuo (2011) reported that a springtime soil moisture anomaly over YRNC is closely correlated with the East Asian summer monsoon and JJA rainfall in eastern China. In the present study, a series of numerical experiments was performed using NCEP GCM/SSiB, to investigate the sensitivity of the East Asian summer monsoon and JJA rainfall in China to soil moisture anomalies over YRNC. In addition to a control experiment with free-running soil moisture, sensi-

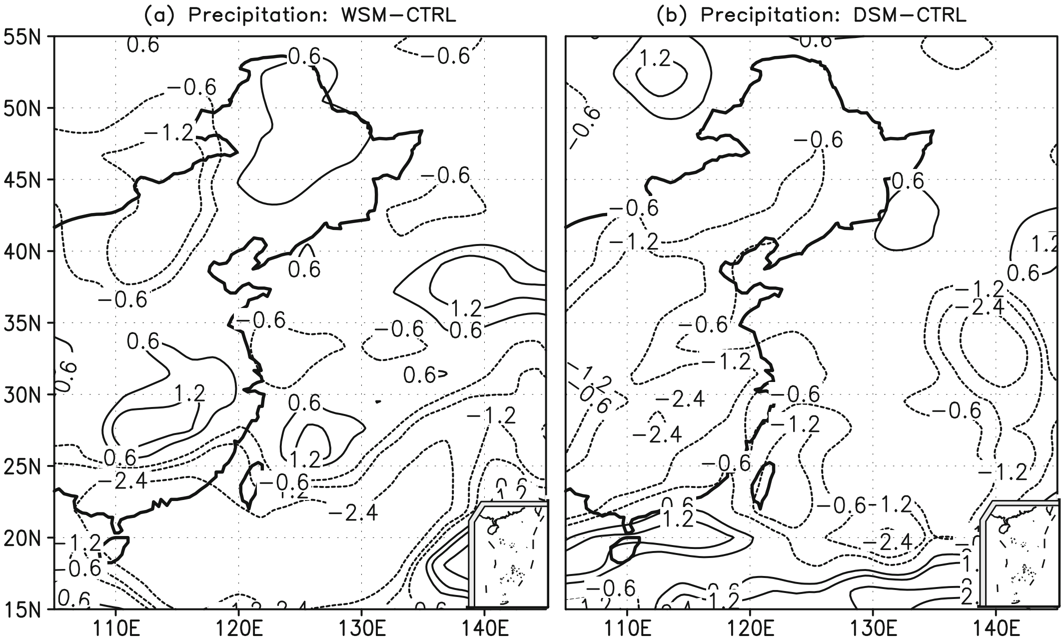

Fig. 11. As in Fig. 9 but for JJA precipitation (units: mm d^{-1}).

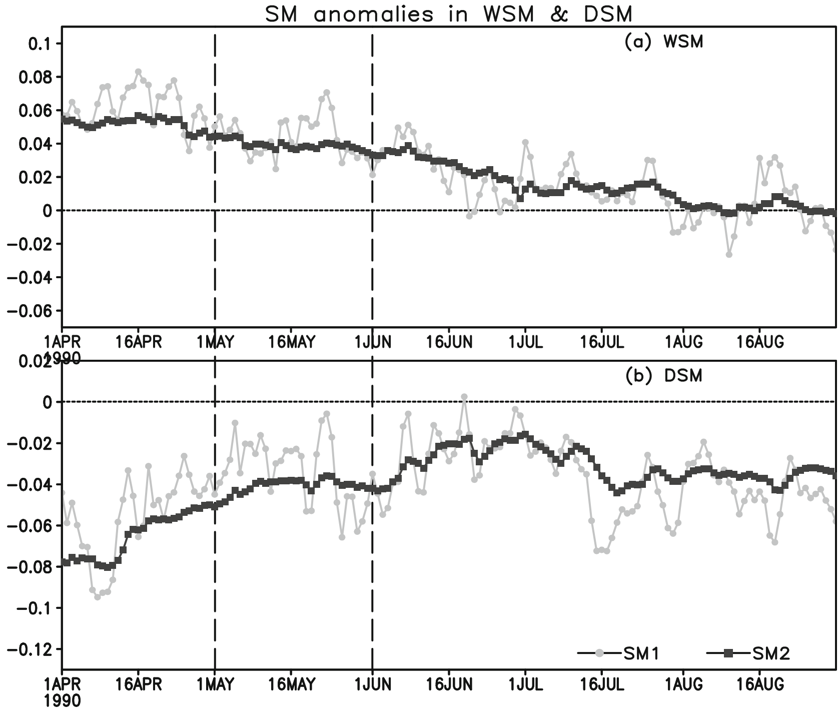

Fig. 12. Time series of the difference in top (grey lines with circles) and deep (black lines with squares) soil moisture between CTRL and (a) WSM and (b) DSM.

tivity simulations were performed with soil moisture values double and half those in the control run.

The results of the experiments indicated that the Asian summer monsoon responds robustly to wet soil anomalies in YRNC. Wet soil is accompanied by colder land temperature via land–atmosphere energy exchange, and the abnormally cold land surface narrows down the land–sea thermal contrast and thereby weaken the East Asian summer monsoon (weaker upper easterly monsoonal flow and low-level westerly monsoonal jet). An anomalous anticyclonic circulation covers southeastern China and thereby less rainfall occurs in the region. In the middle latitudes, wet soil anomalies are associated with a strengthened East Asian trough extending southward to Northeast China, resulting in more rainfall over Northeast China and less rainfall over North China. The abnormally strong southward East Asian trough and weakened

East Asian summer monsoon circulation correspond to the convergence of northerly and southerly flow over the Yangtze River valley, conducive to more precipitation in this region.

The rainfall in JJA in eastern China decreases with negative soil moisture anomalies in YRNC. Dry soil is associated with less latent and more sensible heat flux (i.e., higher Bowen ratios), indicating a higher boundary layer and reduced convective instability and evaporation. Little change occurs in atmospheric moisture convergence over YRNC. These factors correspond to decreasing summer rainfall in YRNC.

We also briefly considered the correlation between tropical SST in the previous winter and springtime soil moisture in YRNC. Analysis showed that, although tropical SST has a major influence on the Asian summer monsoon, soil moisture also contributes in this regard and soil moisture–precipitation feedback reinforces that part of the monsoon not produced by SST anomalies. Nevertheless, it should be noted that, although this study was based on observed facts, it remains difficult to assess the degree to which the numerical results are model-dependent. Further investigations with more numerical simulations are undoubtedly necessary to improve understanding of soil moisture–precipitation feedback.

Acknowledgements. This study was jointly supported by the National Natural Science Foundation of China (Grant Nos. 41205059, 41221064 and 41375092) and the Special Fund for Public Welfare Industry (Meteorology) (Grant No. GYHY201206017).

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