2A.3 SIMULATED IMPACTS OF AGRICULTURAL LAND USE CHANGE ON THE CLIMATE SYSTEMS IN ASIA*

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*This manuscript has been modified from the paper "Simulated impacts of irrigation on the atmospheric circulation over Asia" submitted to *JGR-Atmospheres* (July, 2010).

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1. INTRODUCTION

Globally, the expansion and intensification of agricultural practices have altered our planet's land surface (Ramankutty et al. 2008), and they could accelerate as irrigation activities increase. For instance, croplands and pastures have become one of the largest terrestrial biomes on the planet, rivaling forest cover in extent and occupying ~34% of the Earth's ice-free land surface (Foley et al. 2005; Ramankutty et al. 2008). Irrigated areas have increased rapidly over the last few decades across the world, especially in Asia. Today, about 69% of the total irrigated area of the world is located in Asia, and more than 30% of the cultivated area are equipped for irrigation in the following regions in Asia: South Asia (37.6%), Central Asia (34.9%), and Middle East (30.6%) around the year 2000 (Siebert et al. 2005). Increased irrigation can modify the conditions of surface heat and moisture, and also regional climate as has been shown for the Indian subcontinent (e.g., Douglas et al. 2009), the U.S. (e.g., Adegoke et al. 2003), and Central Asia (Shibuo et al. 2007).

Previous studies have considered irrigation effects as a local or regional climate forcing mainly confined to the near-surface and lower-level atmospheric conditions (e.g., Saeed et al. 2009; Sacks et al. 2009; Douglas et al. 2009; Kueppers et al. 2007; Adegoke et al. 2003). Here, we will explore the impacts of irrigation on summer climate over Asia not only near the surface but also in the mid- and upper-troposphere. We also examine the impacts of irrigation on the atmospheric circulation in the upper-troposphere over Asia.

2. MODEL EXPERIMENTS AND ANALYSIS

We simulated the effects of irrigation on climate using version 3 of CAM (Collins et al. 2004) coupled to version 3.5 of CLM (Oleson et al. 2004). We compared simulations with and without irrigation. Details of the simulations are described by Sacks et al. (2009). We performed two 30-year simulations, one with irrigation and one without. The initial conditions for both simulations were taken from a 150-year spin-up. However, this spin-up was done without irrigation and with the default CLM configuration of all vegetation types sharing a single soil column. Thus, we discarded the first 10 years of each simulation as additional spin-up, and performed comparisons using seasonally-averaged values of the last 20 years. We ran the model using the spectral Eulerian dynamical core at T42 resolution (~ 2.8° × 2.8°), with 26 levels in the vertical and a 20-minute time step. We used climatological sea surface temperatures rather than an ocean model to decrease interannual variability, thus increasing the signal-to-noise ratio of irrigation's effects on climate.

To diagnose the effects of irrigation on the near-surface climate, we examined surface sensible (H) and latent (LE) heat fluxes, and near-surface air (reference height) temperature. Temperatures and geopotential height at multiple levels were used in the meridional cross-section profiles to investigate whether irrigation can affect tropospheric climate. We also calculated layer-averaged tropospheric temperature (Pielke et al. 1998) using the height difference (depth) between two pressure surfaces (i.e., 1000-850 and 1000-200 hPa thickness temperatures) to evaluate the changes in depth-averaged tropospheric temperatures due to irrigation-induced forcing. 200 hPa height and vorticity were used as indicators of the atmospheric circulation in the upper-troposphere. The patterns of horizontal distributions and vertical cross-sections of zonal wind (*u*-wind) were used to examine if there are significant changes in the intensity of westerly and easterly winds over mid-latitude and tropical Asia, respectively, in boreal summer (i.e., Asian jet and Tropical easterly jet).

3. EFFECTS ON THE NEAR-SURFACE CLIMATE

In MAM, about 0.2~2.0 mm/day of water is added through irrigation in parts of Southern Europe, the Tigris-Euphrates river basin in the Middle East, the Amu Darya and Syr Darya river basins in Central Asia, and the Indus river basin in northern India and Pakistan (Fig. 1a). The area of water added through irrigation decreases over Southern Europe and the Middle East in June through August (JJA), but it increases over northern India and Pakistan (Fig. 1b).

In order to understand the effects of irrigation during boreal spring and summer on the near-surface climate in Asia during summer, we examine the changes in surface heat fluxes in JJA. Significant changes in H and LE are simulated over the highly irrigated regions in spring and summer (Figs. 2a and b). Significantly decreased H and increased LE are found over Southern Europe, the Middle East, and Central Asia. Significant changes in surface heat fluxes due to irrigation can impact the surface temperature (e.g., Douglas et al. 2009). The differences in near-surface air temperature between the irrigated and non-irrigated model runs show significant changes over Southern Europe, the Middle East, and Central Asia in JJA (Fig. 2c). Surface air temperature decreases by as much as 1 K over the Middle East and Central Asia.

4. EFFECTS ON THE UPPER-LEVEL CLIMATE

The irrigation cooling effect is not confined to the near-surface atmosphere, but also spreads to the lower-troposphere (Kueppers et al. 2007). Meridional vertical cross-section of JJA temperature differences between the irrigated and non-irrigated simulations is shaded in Fig. 3. They are zonally averaged over the Middle East and Central Asia (30°~80°E) – the regions where surface heat fluxes and near-surface temperature are significantly changed in the irrigation runs. A strong irrigation-induced cooling over 35°~40°N (up to 0.8 K) spreads to adjacent regions and the lower-troposphere, and it is statistically significant over 30°~45°N up to 650 hPa. Thus, the irrigation-induced cooling over the Middle East and Central Asia spreads out both horizontally and vertically, and reaches almost to the mid-troposphere.

This significant cooling in the lower-troposphere over the irrigated regions can induce a decrease of layer-averaged tropospheric temperatures. The averaged temperature between 1000-850 hPa layer is significantly decreased by up to 0.8 K over the Middle East and 0.6 K over Central Asia (Fig. 4a), and its spatial distribution is similar to that of the difference of near-surface temperature shown in Fig. 3c. For 1000-200 hPa layer-averaged temperature, a significant cooling is shown over eastern Middle East and Central Asia decreased by up to 0.3 K (Fig. 4b).

A cooling in the layer-averaged temperature in the troposphere due to the irrigation-induced cooling in the lower-troposphere can affect the geopotential height in the troposphere over the irrigated regions, because the thickness of the corresponding layer (the height difference between two pressure surfaces) is related to the averaged temperature of the layer

(Pielke et al. 1998). A significant decrease of the height in the troposphere is simulated in the irrigation case as shown in the meridional cross-section of height averaged over the Middle East and Central Asia, 30°~80°E (Fig. 5). Significant changes in height are shown over the meridional regions of 30°~45°N, which are consistent with the regions of significant irrigation-induced cooling in the lower-troposphere shown in Fig 3. In addition, the core of the significant decrease in height is in 200 hPa level over the regions of strong irrigation-induced cooling in the lower-troposphere (~40°N). The analyses of the layer-averaged temperatures and height in the troposphere support that the irrigation-induced cooling impacts summer climate not only near the surface but also in the upper-troposphere over the Middle East and Central Asia.

5. IMPACTS ON THE ATMOSPHERIC CIRCULATION

Some modeling studies have found that the changes in the atmospheric circulation by tropical deforestation can modify the large-scale climate system in mid- and high-latitudes (e.g., Chase et al. 2000). Here we investigate if the changes in tropospheric height by the irrigation-induced cooling in the troposphere can modify the atmospheric circulation over the Middle East and Central Asia, which might result in the change of the large-scale climate system in Asia. The atmospheric circulation over Asia in boreal summer is dominated by a huge anti-cyclone over the tropical to mid-latitude Africa-Asian regions (Ding 1994). The climatology of the upper anti-cyclonic circulation in JJA corresponds to the upper-level westerly winds to the north of 30°N (Asian jet) and easterly winds to the south of 20°N (Tropical easterly jet). The jet streams are one of the most important circulation features that affect the monsoon activity and precipitation in the African and Asian regions (Ding 1994).

Upper atmospheric circulation over the irrigated regions is significantly changed as shown in the differences of height, vorticity, and wind vectors between the irrigated and control runs (Figs. 6 and 7). For instance, significantly negative differences of height (Fig. 6a) and positive differences of vorticity (Fig. 7a) at 200 hPa are shown over the Middle East and Central Asia where the climate near the surface and in the troposphere is significantly changed in the irrigated runs. The differences in height and vorticity affect the atmospheric circulation in the upper-troposphere, and thus there are cyclonic wind differences around the negative height and positive vorticity differences across northern Africa and Central Asian region. The cyclonic circulation differences weaken the anti-cyclonic circulation over the Africa-Asian region (see wind vectors in Figs. 6 and 7), and the weakening might result in the change of zonal wind pattern in upper atmosphere.

Significant negative differences of 200 hPa westerly wind (i.e. easterly wind difference) located at 40°~55°N mostly over the irrigated regions (Fig. 8a) cause a weakening of strong westerly winds (Asian jet) over the same region, which its maximum reaches a wind speed of 35 m/s (Fig. 8b). A significant weakening of the Asian jet appears over 40°~55°N across Eastern Europe and Central Asia (Fig. 8a). In order to examine the change in the tropical easterly jet with a maximum intensity around at 100 hPa, we calculated the *u*-wind differences at 100 hPa with control (Figs. 8c and d). A significant weakening of the tropical easterly jet is found in the irrigated runs over 40°~70°E and 10°~30°N in the south of the irrigated regions, which is caused by the westerly wind from the cyclonic circulation difference.

The differences of *u*-wind between the irrigated and control runs are zonally averaged over the Middle East and Central Asia (30°~80°E) in JJA– the same regions where the meridional cross-sections of temperature (Fig. 3) and height (Fig. 5) are calculated. A weakening of westerly winds is significant from the lower- to upper-troposphere over 45°~55°N with a decrease of wind speed more than 2.5 m/s in the core of Asian jet around at 200 hPa (Fig. 9a). These results suggest that the irrigation-induced forcing can weaken the strength of Asian jet by ~10% of its maximum wind speed in control runs (~30 m/s).

6. CONCLUSIONS

This study finds that simulated irrigation impacts the climate near the surface as well as in the upper-troposphere over the irrigated regions. In addition, these irrigation-induced changes could affect the atmospheric circulation over Asia and, in turn, jet streams over the irrigated and surrounding regions.

The effects of irrigation on the near-surface climate are significant over parts of major river basins in the Middle East (Tigris-Euphrates river basin) and Central Asia (Amu Darya and Syr Darya river basins) during boreal summer. Decreased sensible heat and increased latent heat fluxes lead to significant cooling in surface air temperature. The irrigation cooling effect is not confined to the near-surface, but rather spreads to the lower-troposphere and reaches almost the mid-troposphere. We find that irrigation could significantly decrease temperature in the lower-troposphere, by 0.1~0.8 K over the Middle East and Central Asia in JJA. The irrigation-induced cooling in the lower-troposphere causes a decrease in the layer-averaged temperature between two pressure surfaces in the troposphere (thickness temperature), and in turn it leads to a decrease in tropospheric height over the irrigated regions. In the model simulations, the differences of the averaged temperatures in 1000-850 and 1000-200 layers between the irrigated and control runs show significant cooling in the troposphere over the Middle East and Central Asia. Thus, a cooling in the depth-averaged temperature results in a significant decrease in tropospheric height over the irrigated regions.

These results suggest that irrigation activities can impact the atmospheric circulation over the Middle East and Central Asia through the changes in tropospheric height due to the irrigation-induced cooling in tropospheric layers. In boreal summer, cyclonic differences of upper-level winds are found around the negative differences of upper-level height (lower height) across northern Africa and Central Asian region. Consistently, the positive upper-level vorticity over the same region is simulated in the difference between the irrigated and control runs. The cyclonic differences weaken the atmospheric circulation over the irrigated and surrounding regions, which is a strong anti-cyclonic circulation over the tropical to mid-latitude Africa-Asian regions. These changes lead to a weakening of the westerly Asian jet located over the irrigated regions, and to a weakening of the tropical easterly jet over the south of the irrigated regions. The meridional cross-section of *u*-wind supports a significant weakening of the Asian jet (~2.5 m/s at 200 hPa) by ~10% of its maximum wind speed (~30 m/s). A decrease of the tropical easterly jet is significant in the 100~200 hPa layer, but the magnitude of the weakening (0.5~1 m/s) is less than that in the Asian jet. These changes in the jet streams over Asia due to irrigation might induce a large impact on Asian summer climate through the changes in monsoon activity and precipitation in Asia. The overall physical and dynamic effects of irrigation on the atmospheric circulation over Asia are shown in Fig. 10.

7. REFERENCES

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8. FIGURES

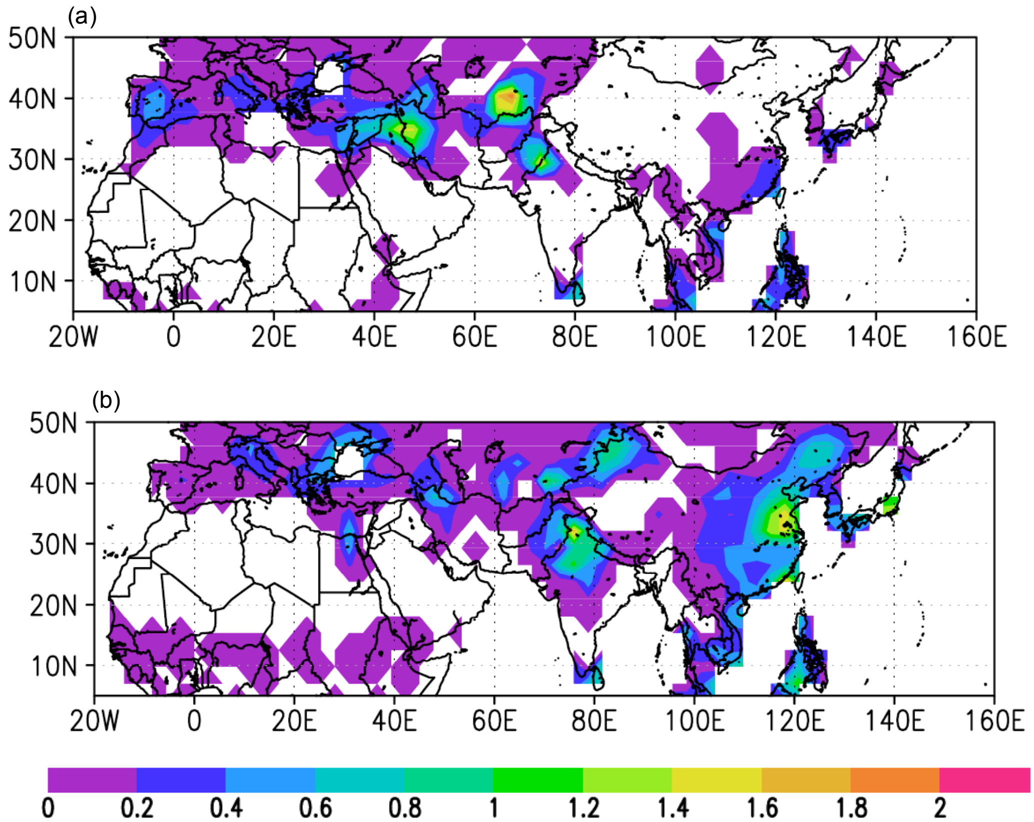


Fig. 1 Seasonally-averaged differences of water added through irrigation (mm/day) between the irrigated and non-irrigated model runs for (a) MAM and (b) JJA.

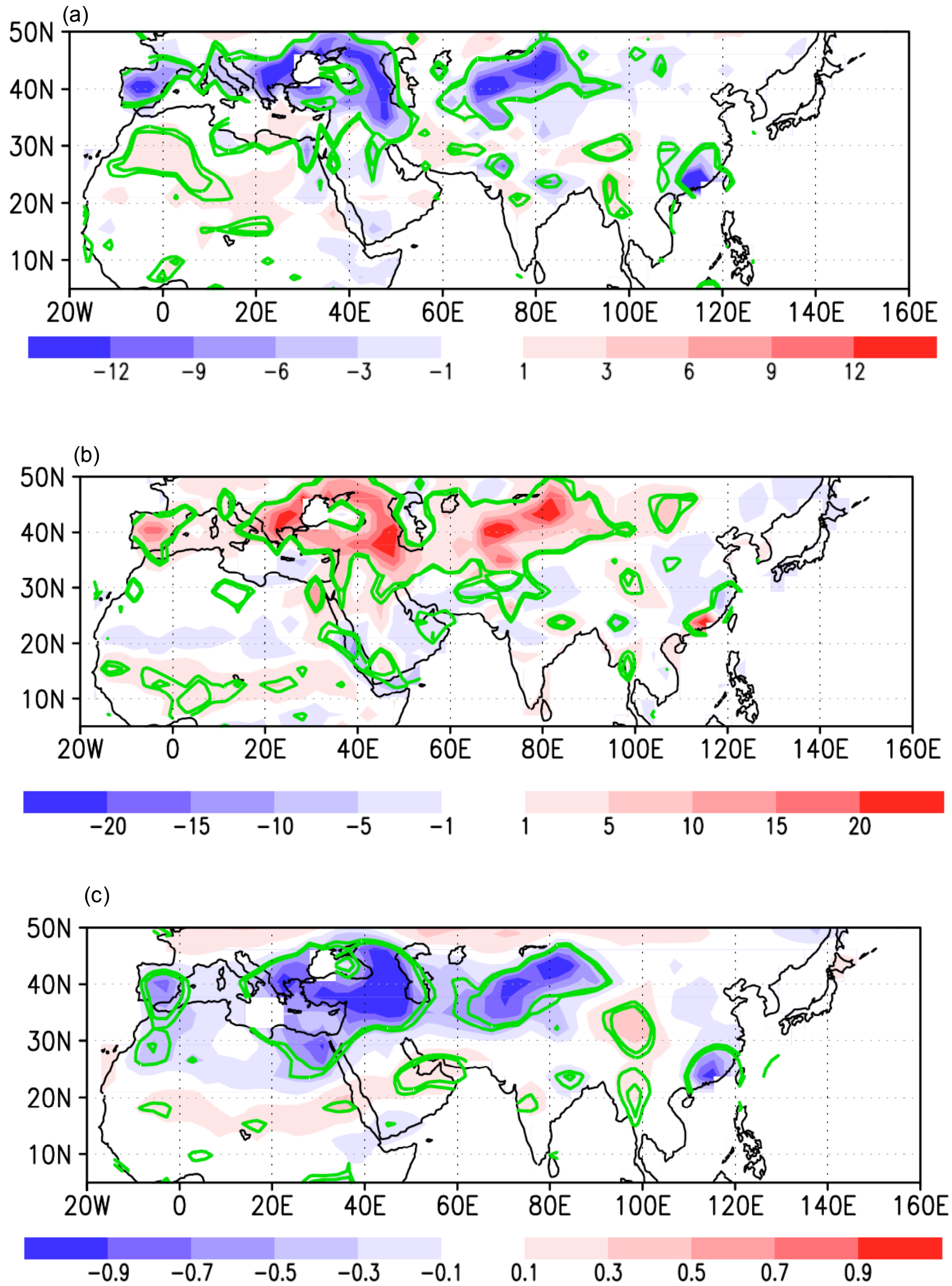


Fig. 2 Differences of (a) surface sensible (H) and (b) latent (LE) heat fluxes (W/m^2), and (c) reference height temperature (K) between the irrigated and non-irrigated model runs for JJA. Significantly different regions at the 90 and 95% levels are contoured in green (same as in all figures for the differences).

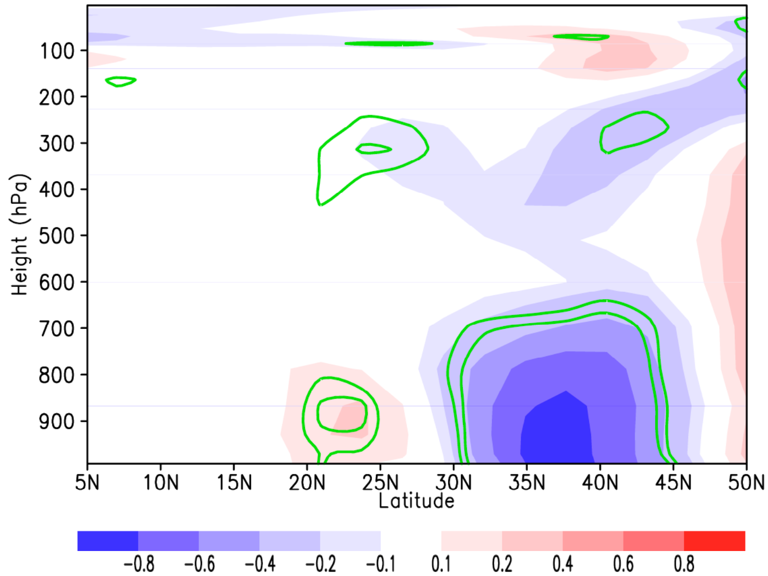


Fig. 3 Meridional cross-sections of differences of temperature (K) between the irrigated and non-irrigated model runs zonally averaged over 30°~80°E for JJA.

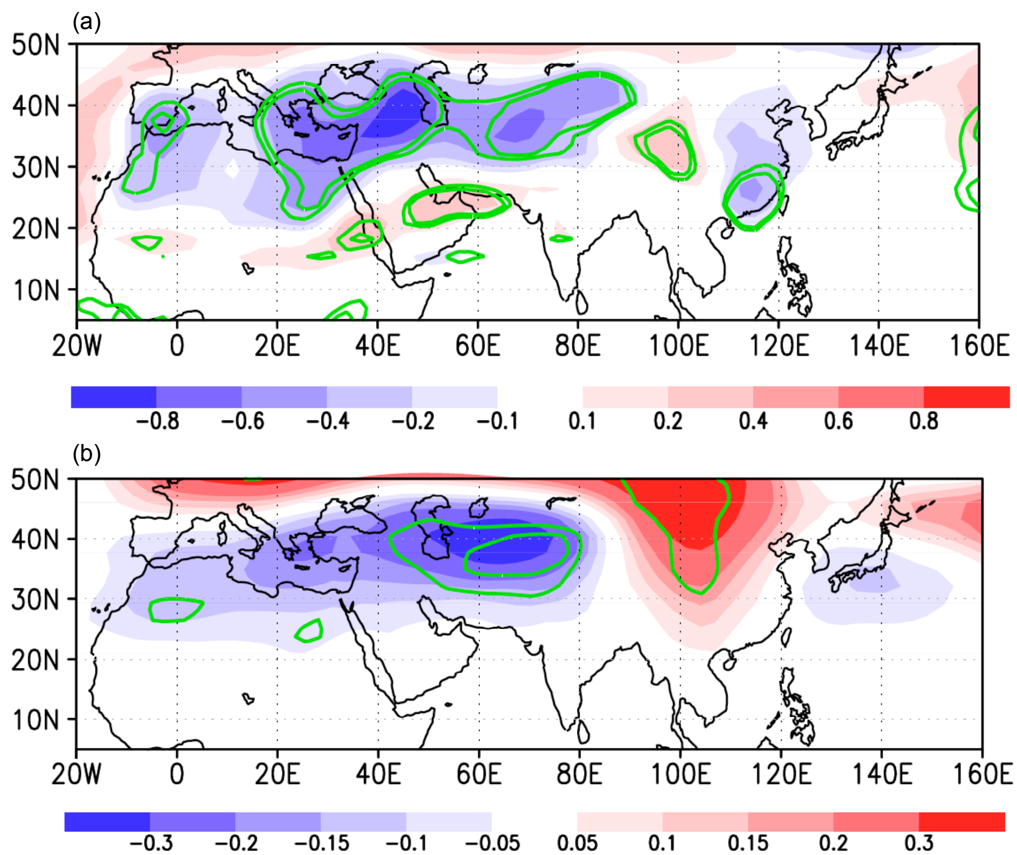


Fig. 4 Differences of layer-averaged temperature (K) between the irrigated and non-irrigated model runs for JJA. The averaged temperature is calculated from the height difference between two pressure surfaces - (a) 1000-850 and (b) 1000-200 hPa layers.

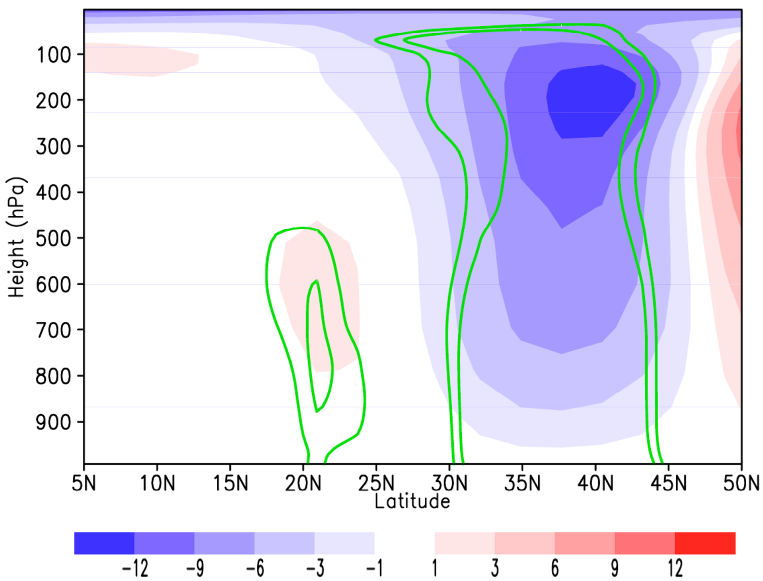
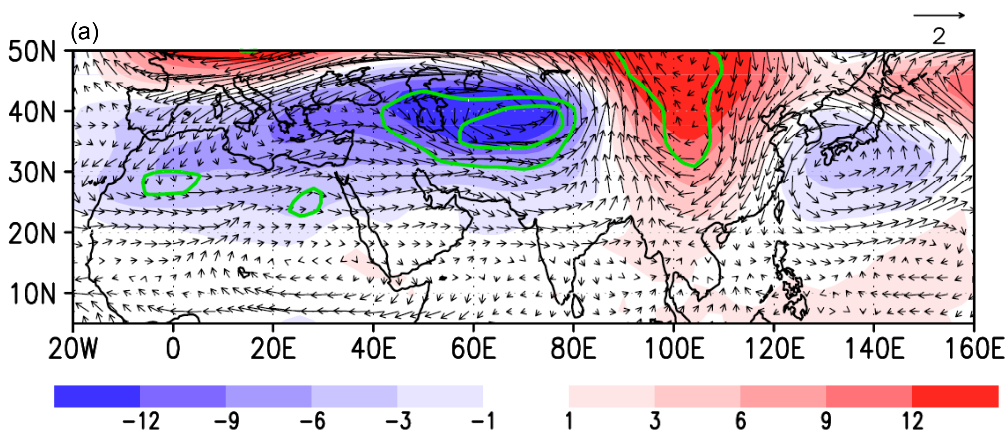


Fig. 5 Meridional cross-sections of differences of height (m) between the irrigated and non-irrigated model runs zonally averaged over 30°~80°E for JJA.



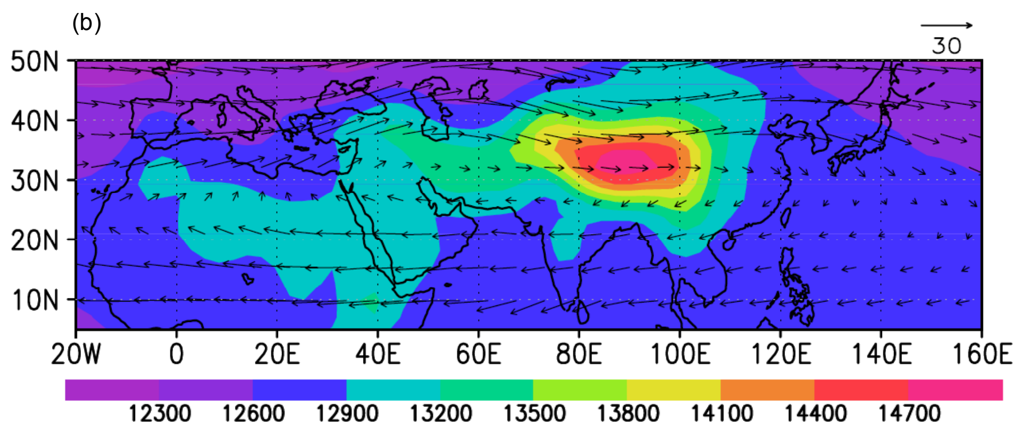


Fig. 6 (a) Differences of height (m; shaded) and wind vectors (m/s) at 200 hPa between the irrigated and non-irrigated model runs and (b) their control runs for JJA.

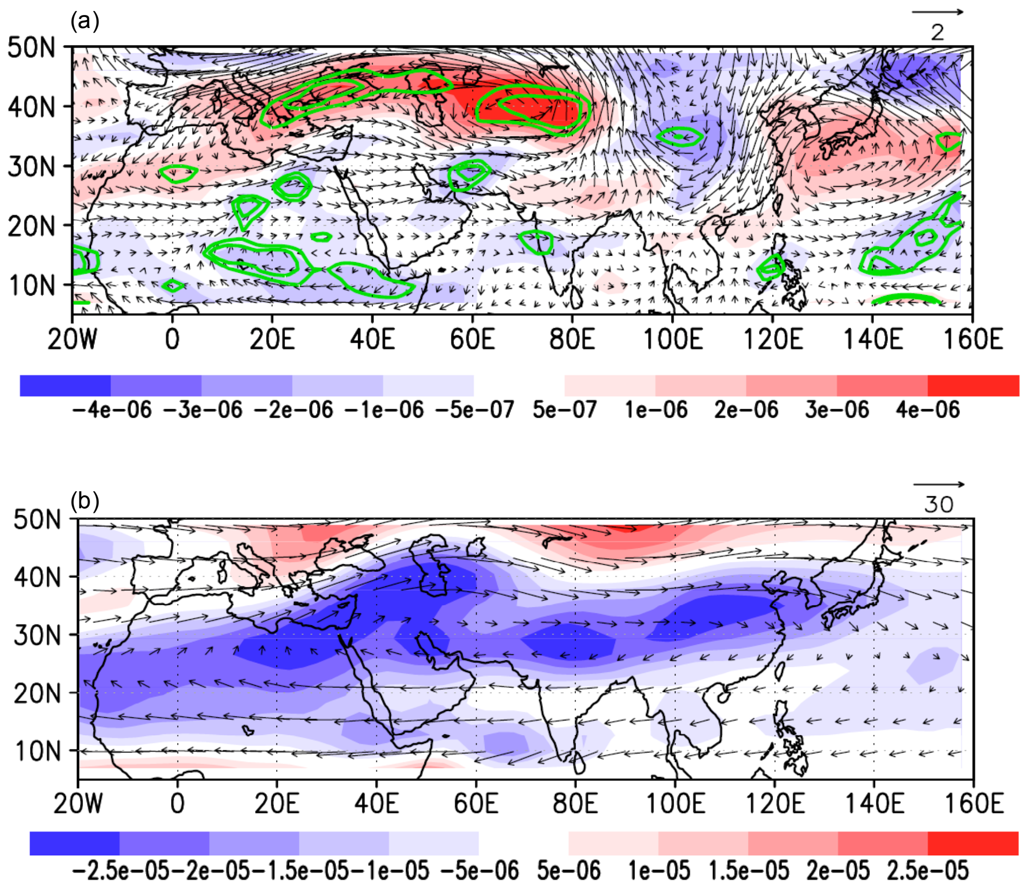


Fig. 7 (a) Differences of vorticity (1/s; shaded) and wind vectors (m/s) at 200 hPa between the irrigated and non-irrigated model runs and (b) their control runs for JJA.

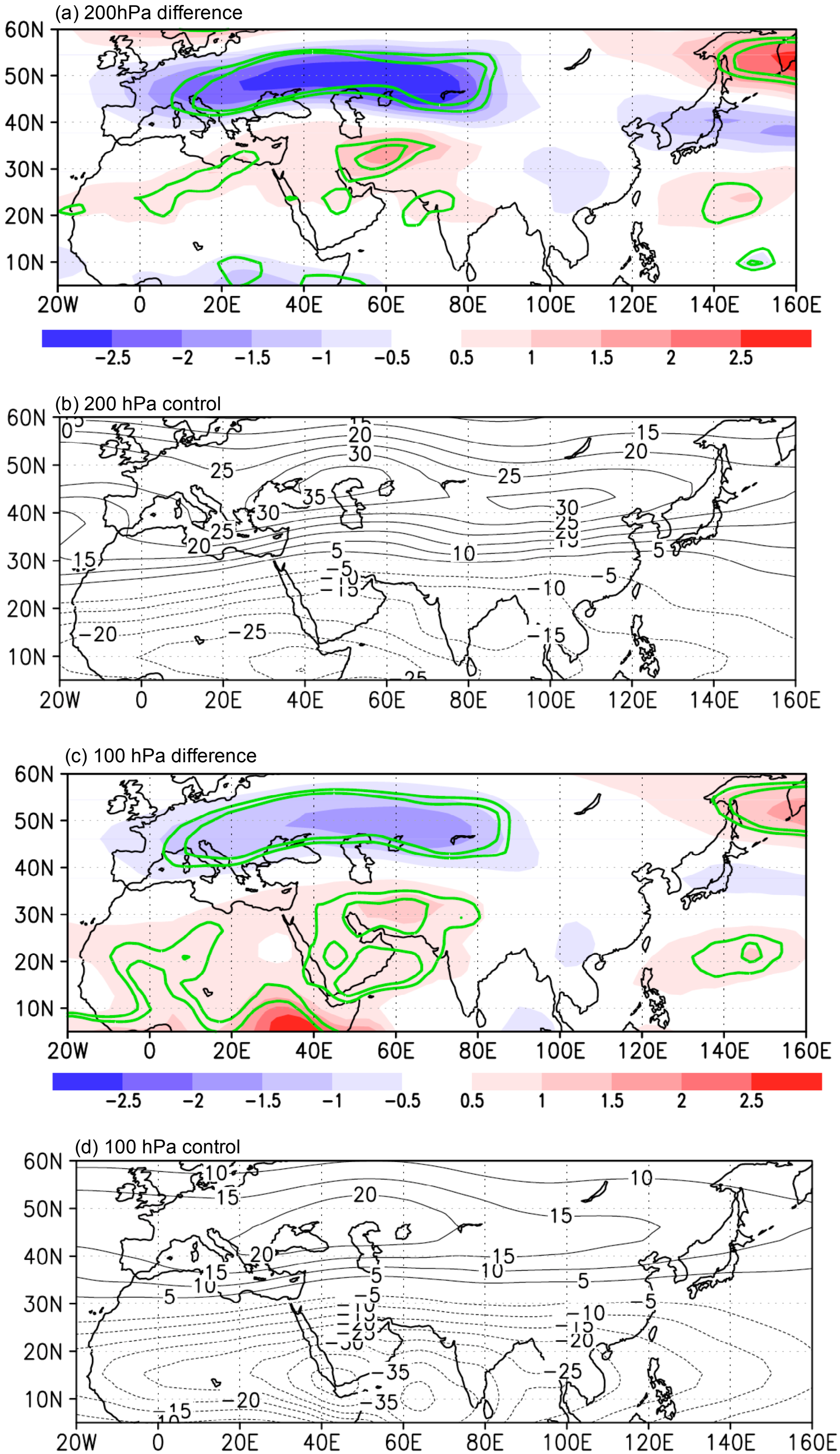

(a) 200hPa difference
(b) 200 hPa control
(c) 100 hPa difference
(d) 100 hPa control
60N
50N
40N
30N
20N
10N
20W
0
20E
40E
60E
80E
100E
120E
140E
160E
−2.5
−2
−1.5
−1
−0.5
0.5
1
1.5
2
2.5

Fig. 8 Differences of zonal wind (*u*-wind; m/s) at (a and b) 200 and (c and d) 100 hPa between the irrigated and non-irrigated model runs (left column) and their control runs (right column) for JJA.

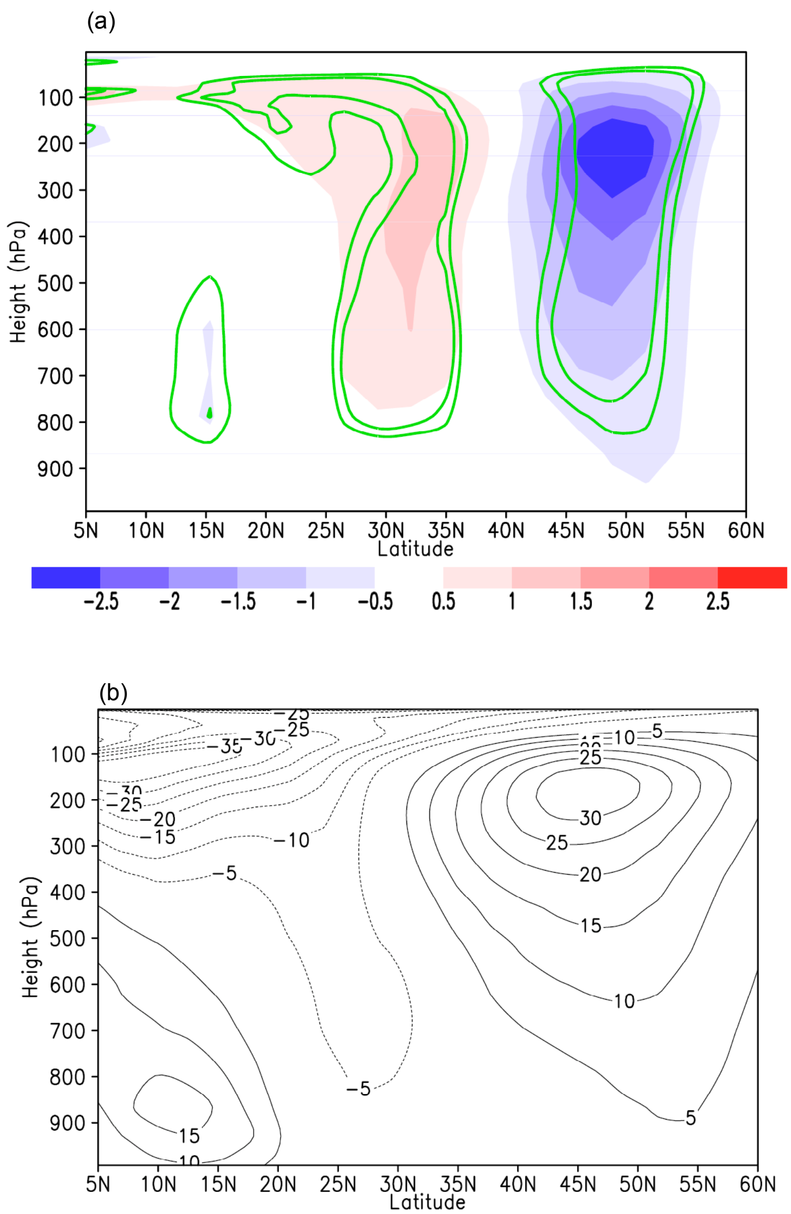


Fig. 9 Meridional cross-sections of (a) differences of zonal wind (*u*-wind; m/s) between the irrigated and non-irrigated model runs and (b) their control runs zonally averaged over 30°~80°E for JJA.

Irrigation over the Middle East and Central Asia in boreal spring and summer

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A decrease in sensible heat and an increase in latent heat fluxes in summer

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A cooling of both the surface and the lower-troposphere

↓

A decrease in the layer-averaged temperature in the troposphere

↓

A decrease in the tropospheric height

↓

A weakening of the upper-level anti-cyclonic circulation

↓

A weakening of Asian jet in summer

Fig. 10 Physical and dynamic effects of irrigation on the atmospheric circulation over Asia.