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Key Points:

- Model simulation without considering irrigation underestimates ET over Indo-Gangetic Plain
- Irrigation at Asian low latitudes has the potential to induce PNA teleconnection
- Irrigation results in interhemispheric thermal gradient, thereby modifying Pacific subtropical jet

Supporting Information:

- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7
- Figure S8
- Texts S1–S4

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Potential impacts of wintertime soil moisture anomalies from agricultural irrigation at low latitudes on regional and global climates

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Abstract Anthropogenic water management can change surface energy budgets and the water cycle. In this study, we focused on impacts of Asian low-latitude irrigation on regional and global climates during boreal wintertime. A state-of-the-art Earth system model is used to simulate the land-air interaction processes affected by irrigation and the consequent responses in atmospheric circulation. Perturbed experiments show that wet soil moisture anomalies at low latitudes can reduce the surface temperature on a continental scale through atmospheric feedback. The intensity of prevailing monsoon circulation becomes stronger because of larger land-sea thermal contrast. Furthermore, anomalous upper level convergence over South Asia and midlatitude climatic changes indicate tropical-extratropical teleconnections. The wintertime Aleutian low is deepened and an anomalous warm surface temperature is found in North America. Previous studies have noted this warming but left it unexplained, and we provide plausible mechanisms for these remote impacts coming from the irrigation over Asian low-latitude regions.

1. Introduction

Soil moisture is a crucial component in the terrestrial hydroclimate and ecological system. The temporal and spatial distribution of soil moisture is pivotal for synoptic weather prediction and large-scale climate simulation. Studies have shown that soil moisture can contribute to intraseasonal forecast skill [e.g., *Koster et al.*, 2010]. The importance of soil moisture lies in its control of both surface energy balance and water balance [*Seneviratne et al.*, 2010]. Liquid soil water is transformed into water vapor in the process of evapotranspiration (ET) as the atmosphere absorbs latent heat from local land surfaces and can release the energy elsewhere. Depending on atmospheric circulation and conditions, the condensation of vapor results in cloud formation or in precipitation, which returns the water to the land surface. Coupled with air temperature and precipitation, soil moisture can therefore interact with the climate.

Through various types of land use, humans are considerably influencing land surfaces. Among them, irrigation is the most direct act of changing soil moisture. Adding water to a field to maintain soil moisture higher than unmanaged land causes evaporation from bare soil and transpiration from crops to increase. Previous studies have shown that irrigation has first-order effects on the near-surface climate through changes in local surface energy partitioning [e.g., *Douglas et al.*, 2006] and generally leads to a lower Bowen ratio over the land, where the latent heat flux at the surface is increased and the sensible heat flux is decreased. Observations have also shown that air temperatures over heavily irrigated regions are typically lower because of evaporative cooling effects [e.g., *Bonfils and Lobell*, 2007; *Sen Roy et al.*, 2007]. Atmospheric model simulations have demonstrated that irrigation results in surface cooling and potentially enhances downwind precipitation [*Sacks et al.*, 2009; *DeAngelis et al.*, 2010; *Puma and Cook*, 2010; *Cook et al.*, 2011]. In addition, modeling studies have revealed that irrigation affects atmospheric circulation in monsoonal regions including North America [*Lo and Famiglietti*, 2013; *Lo et al.*, 2013], West Africa [*Im et al.*, 2014], and South Asia [*Saeed et al.*, 2009; *Lee et al.*, 2011a; *Guimberteau et al.*, 2012; *Shukla et al.*, 2014], because these places are in climatic transition zones and are more sensitive to soil moisture deviations resulted from stronger land-atmosphere coupling strength [e.g., *Koster et al.*, 2006].

South Asia is the most heavily irrigated region of the world. Previous studies have shown that the intensity [*Saeed et al.*, 2009], variability [*Shukla et al.*, 2014], and onset date [*Guimberteau et al.*, 2012] of the summer monsoon are possibly affected by irrigation. Irrigation introduces additional moisture to the atmosphere; concurrently, evaporative cooling changes the thermal contrast between land and the ocean, thereby affecting moisture transport and the summer monsoon circulation. Studies so far focused on the impacts of irrigation during summertime mostly; however, high soil moisture anomalies from irrigation might persist through fall and winter, and farmers still irrigate in low-latitude regions in the wintertime when the cool, dry air flows southward from the Indian subcontinent to the Indian Ocean as the prevailing South Asian winter monsoon. We investigated the extent to which the high soil moisture anomalies of the wintertime as a result of the substantial amount of irrigation water added to fields affect the climate. Recently, *Alter et al*. [2015] have also pointed out the influence of irrigation in Sudan on rainfall patterns using both observations and regional climate model. However, the use of regional climate model and prescribed sea surface temperature limits the simulated impacts on multiscale interactions (e.g., monsoon and Intertropical Convergence Zone) and the remote teleconnections. The current study thus focuses on identifying the land-atmosphere interaction processes affected by water management and the consequent responses in atmospheric circulation over South Asia during the winter. We carry out this study via model observation comparisons and state-of-the-art coupled Earth system model simulations.

2. Data and Model

In this study, two sets of land surface ET data were used for the analysis. One is a satellite-derived land ET record [*Zhang et al*., 2010] based on advanced very high resolution radiometer (AVHRR) at a 0.5° × 0.5° resolution, and the other is a more in situ-based data set upscaled from the FLUXNET eddy covariance towers using a machine learning approach (i.e., model tree ensemble approach) and is also at 0.5° × 0.5° resolution [*Jung et al*., 2009]. Also used are the potential evapotranspiration (PET) data from the Climate Research Unit time series 3.2 data [*Harris et al*., 2014] and the data of irrigation water demand derived from agriculture and climate data sets [*Wisser et al*., 2008]. To isolate the effects of irrigation on the climate from other anthropogenic factors, we make use of the historical run of the National Center for Atmospheric Research Community Earth System Model (CESM) from the Coupled Model Intercomparison Project Phase 5 output archives. The model resolution is 0.9° × 1.25°, and in this historical run, all the major anthropogenic forcings in the 20th century are included in the simulation but not the irrigation. Therefore, the irrigation effects on the climate are identified by comparing the historical run with observations.

Numerical experiments were also conducted with the CESM to understand the mechanisms that enable irrigation to affect local and remote climates and the associated changes in atmospheric circulation. The experiments were performed with a fully coupled land-ocean-atmosphere configuration of the CESM [*Hurrell et al*., 2013], which includes the Community Land Model Version 4 that can explicitly simulate land hydrological processes, and the atmospheric component is Community Atmosphere Model Version 5. A control (CTR) simulation and a perturbed (IRR) experiment were conducted, in which the global distribution and amount of irrigation estimated by *Wisser et al*. [2008] over the last decade of the 20th century was included in the experiment but not in the control simulation. The irrigation is applied to the top layer of soil as effective precipitation, with a quarter of the irrigation water being supplied by an unconfined aquifer (details about the methodology of irrigation in the simulation are given in the supporting information). Both simulations were integrated for 100 years with a horizontal model resolution of 1.9° × 2.5°. The first 50 years were used as a model spin-up, whereas the last 50 years were used for analysis.

The ERA-Interim reanalysis data [*Dee et al*., 2011] and Coupled Model Intercomparison Project phase 5 (CMIP5) Community Climate System Model version 4 (CCSM4) last millennium (LM) simulations [*Landrum et al*., 2013] are also used to analyze the influences of South Asia on remote climates.

3. Results

3.1. Regional Impacts Induced by the Irrigation Over the Indo-Gangetic Plain

Boreal winter is generally not the crop growth season at northern midlatitudes because of low temperatures. The temperature is amenable at low latitudes to growing crops; however, it is the dry season, and irrigation is needed to compensate for the lack of moisture. Figure 1a shows a global estimate of irrigation water demand from agricultural and climate data sets [*Wisser et al*., 2008]. Irrigation is concentrated in a few places (especially in South Asia) in boreal winter (January, February, and March; JFM). The belt of irrigation clearly

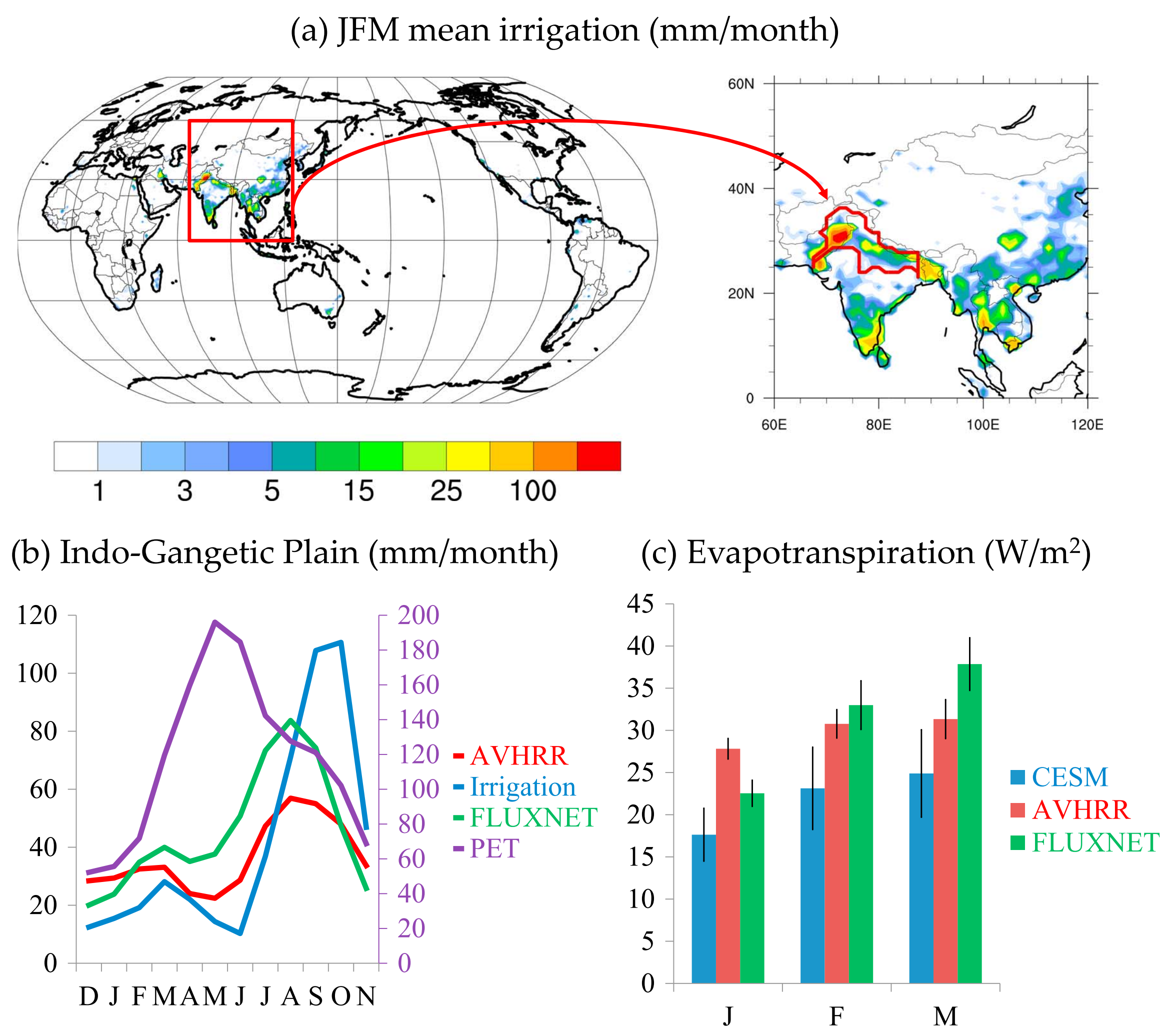

Figure 1. (a) January to March mean irrigation amount (mm/month). The location of the IGP is also shown. (b) Climatological means of AVHRR- and FLUXNET-based ET, irrigation amount, and PET averaged for the IGP (mm/month). The *y* axis label on the right-hand side (in purple) is for PET (also in purple). (c) Simulated IGP mean ET from the CESM and compared with the two observation products (W/m^2). The error bars indicate one standard deviation over the data period. The model resolution is 0.9° × 1.25° and the observations are 0.5° × 0.5°.

observed over northern India is the Indo-Gangetic Plain (IGP), which can be seen having the irrigation amount about an order of magnitude larger than elsewhere. A substantially large amount of water used there is attributed to the practice of flood irrigation, which floods the field to facilitate soaking the soil with water. The flooded fields behave like ponds and continuously evaporate moisture into the lowest level of the atmosphere.

PET is the amount of evapotranspiration the surface would supply if there is sufficient water, whereas the actual ET is limited by the supply of soil moisture. In regions where the PET is higher than the actual ET, previous studies have indicated that there is possibly a direct effect of increased latent heat fluxes to the atmosphere in response to excess soil moisture [e.g., *Seneviratne et al.*, 2010]. In addition, in this region, a considerable portion of the irrigation water is withdrawn from groundwater. As groundwater (particularly confined groundwater) is originally inactive in the water cycle, the withdrawal is thus in effect adding additional water to participate in land-atmosphere interactions.

Irrigation constitutes a critical part of moisture supply to the ET; Figure 1b shows a comparison of the mean seasonal cycles of PET, observed ET, and irrigation amount in the IGP. The irrigation amount, AVHRR-based ET, FLUXNET-based ET, and PET data from CRU are averaged over 1991–2000, 1983–2006, 1982–2011, and 1981–2000, respectively. While the PET curve is unimodal and peaked in the early summer, both the irrigation amount and actual ET curves are bimodal and peaked in spring and early fall. This characteristic is unique and not found in other major river basins in the world (see SI for detailed comparisons). The similarity between the irrigation amount and the ET illustrates the crucial role that irrigation plays in the ET. Furthermore, without considering the effect of irrigation, the ET simulated by the historical run of the CESM in JFM (averaged over 1981–2000) is underestimated compared with that estimated by both remote sensing and in situ observations (Figure 1c). Therefore, the large amount of irrigation water applied in the IGP has most likely left a fingerprint in local water and energy balance that can act as a potential forcing to regional or even remote climate.

To identify the local climate response to South Asia irrigation, we compared the simulation differences between the CTR and IRR simulations in JFM. The results are shown in Figure S2 in the supporting information. Over the South Asia, the irrigation increases the soil water in the top 10 cm of the soil layer (Figure S2a) and the latent heat fluxes into the atmosphere (Figure S2b). The mean latent heat release in the IGP changed from 25.92 W/m^2 in the CTR simulation to 37.74 W/m^2 in the IRR simulation. The latter value is reasonably close to the value of the observed latent heat flux shown in Figure 1c. We note that the largest increases of soil water and latent heat fluxes occur in the heavily irrigated regions (cf. Figures S1a and S1b to Figure 1a). Since the South Asia is located in the subsidence branch of the Hadley circulation during the boreal winter, the increased input of the moisture to the atmosphere by the irrigation does not induce more precipitation locally, which has been implied by previous studies [*Harding and Snyder*, 2012a, 2012b]. By contrast, low-level cloud cover increases downwind of the irrigated regions (Figure S2c). The increased cloudiness decreases the downward solar radiation at the surface (Figure S2d) to cause a surface cooling that spreads throughout the entire Indian subcontinent (Figure S2e). The current results are quite different in comparison with previous studies showing increased precipitation locally or downwind of irrigated regions [e.g., *DeAngelis et al*., 2010]. The different results might to some extent be model dependent, but it also implies that the local responses to irrigation are not always the same and dependent on the background climate and season it is applied.

The intensity of the Indian monsoon circulation is associated with the land-sea thermal contrast between the Indian subcontinent and the Indian Ocean. Therefore, the cooling induced by the irrigation over the Indian subcontinent can result in a larger sea-land contrast to enhance the winter Indian monsoon. This is confirmed by simulation difference produced by the CTR and IRR simulations in Figure 2a, which shows the low-level (925 hPa) northeast winds intensified over northeast South Asia and the western Arabian Sea. The anomalous northeasterlies move across the equator into an anomalous low over the tropical western Indian Ocean, where the upward vertical velocity and precipitation are enhanced. The monsoonal flow then returns northward in the upper troposphere (at 200 hPa; Figure 2b) and subsides over the India Peninsula. The anomalous meridional circulation associated with this enhanced winter monsoon circulation is shown in Figure 2c, where the zonally averaged (40°E–90°E) omega velocity is shown. The figure shows that descending motion is enhanced over the northern India (around 30°N), while the ascending motion is enhanced over the South Indian Ocean (around 30°S). The 200 hPa velocity potential anomalies shown in Figure 2e clearly indicate an anomalous convergence over South Asia and an anomalous divergence over the tropical Indian Ocean. These features together indicate that the IGP irrigation can induce an intensified winter monsoonal circulation and local Hadley cell, which are illustrated in Figure 2d.

3.2. Remote Impacts on the North American Winter Climate

3.2.1. Atmospheric Teleconnection Pattern

In a seminal paper on atmospheric teleconnection patterns associated with barotropic wave propagation and instability, *Simmons et al*. [1983] found that forcings from Southeast Asia are effective sources having large perturbations over the Pacific (see their Figure 5). As shown in Figure 2e, an anomalous convergent center is presented at 200 hPa over South Asia; the low-frequency circulation anomalies are excited through the normal mode instability of the climatological basic state as indicated in *Simmons et al*. [1983]. Figure 3a shows the differences in 200 hPa stream function of CTR and IRR simulations as well as a snapshot of the stream function of the most unstable normal mode simulated by *Simmons et al*. [1983]. The remarkable similarity between the simulated result of irrigation and the normal mode is clearly seen and shows the Pacific/North American (PNA) teleconnection pattern [e.g., *Wallace and Gutzler*, 1981; *Trenberth et al*., 1998]. The PNA-like pattern, seen in Figure 3b featuring above-average heights in the vicinity of Hawaii and over the intermountain region of North America, and below-average heights located south of the Aleutian Islands, indicates some specific climatic change features in North Pacific winter.

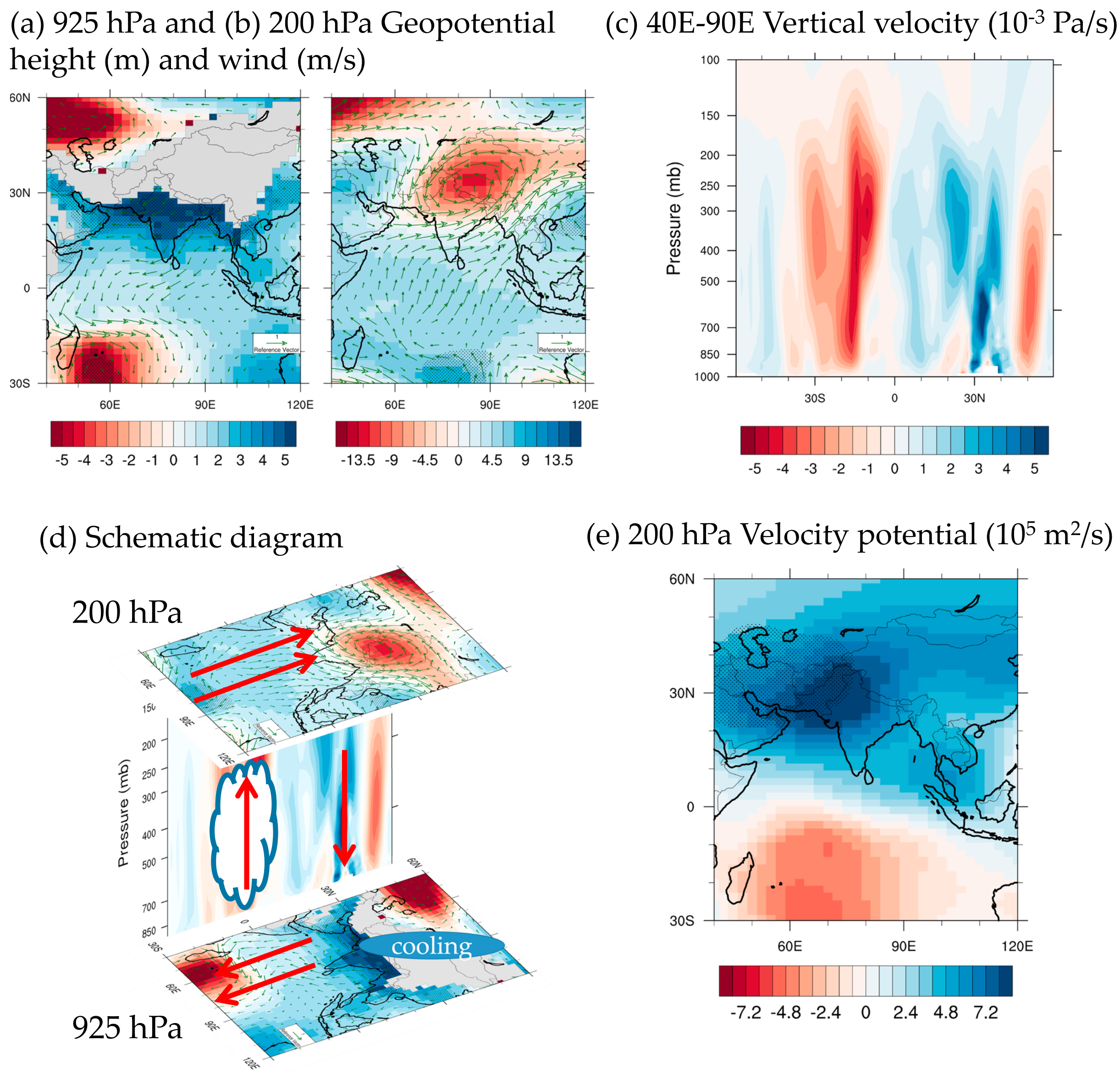

Figure 2. Simulated differences (IRR-CTR) in (a) 925 hPa and (b) 200 hPa geopotential height (shading, m) and wind (vector, m/s); (c) 40°E–90°E mean vertical velocity (10^{-3} Pa/s); (d) schematic diagram showing the process in which irrigation causes monsoon changes; and (e) IRR-CTR 200 hPa velocity potential (10^5 m^2/s) (dotted: $p < 0.1$ for Figures 2a, 2b, and 2e).

Figure 3c shows the differences in surface air temperature over North America between the CTR and IRR simulations, which interestingly exhibit anomalous warming in west to central North America despite the lack of local irrigation in North America during the winter. These differences are manifestation of the remote impacts of irrigation at Asian low latitudes. It is the deepened Aleutian low and ridging across western North America (Figure 3b) associated with the positive PNA-like pattern that results in above-normal temperatures. The warming tendency in North America has also been seen in several previous studies on irrigation impacts [*Sacks et al.*, 2009; *Puma and Cook*, 2010; *Cook et al.*, 2015], which utilized either models or irrigation schemes that are different from the current study. As previous studies did not explicitly explain the origin of the warming tendency in North America, the current study provides a plausible mechanism, which is induced by the irrigation activity in Asian low latitudes.

3.2.2. Interhemispheric Thermal Forcing

On the other hand, we also investigate the zonal mean circulation changes, as we have shown that irrigation is able to have impacts on atmospheric circulation over tropical region (Figure 2). It is known that the intensity

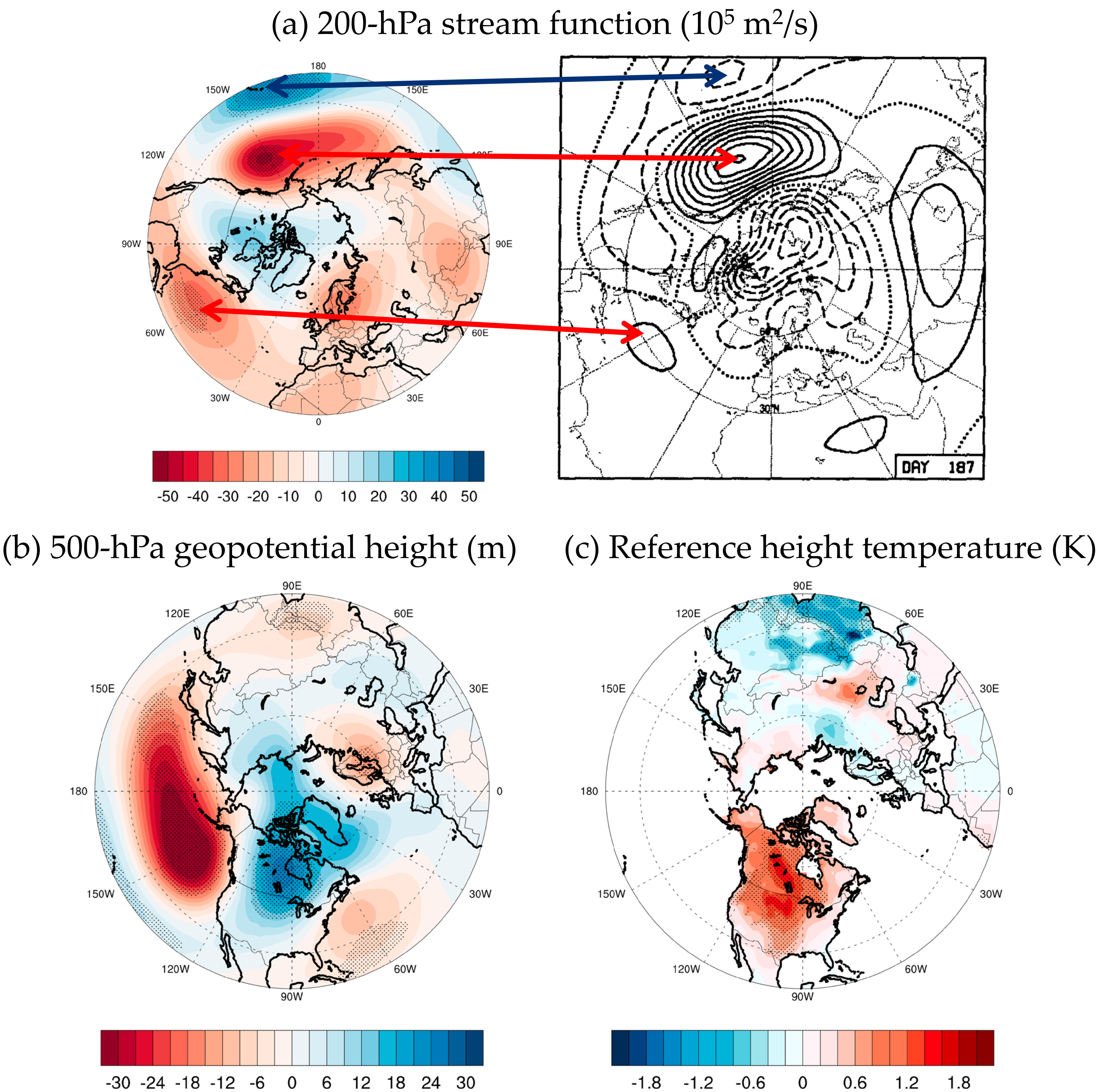

Figure 3. Simulated differences (IRR-CTR) in (a) 200 hPa stream function (10^5 m^2/s); (b) 500 hPa geopotential height (m); (c) reference height temperature over North America (K) (dotted: $p < 0.1$). Also shown is the stream function of the most unstable normal mode in *Simmons et al.* [1983] at a selected day with one-half cycle of the oscillation. The signs of the response are different because in *Simmons et al.* [1983], the sign of the forcing was opposite to ours. Figure reprinted from *Simmons et al.* [1983] with permission from *Journal of the Atmospheric Sciences*.

of tropical Hadley circulation is sensitive to the latitudinal displacement of the solar heating [*Lindzen and Hou*, 1988], which makes the Hadley circulation to be most prominent during boreal winter when the strongest solar displaces to the south of the equator. The Hadley cell transports energy in the direction of its upper branch from the southern hemisphere (SH) to the northern hemisphere (NH) during the winter. The irrigation-induced surface cooling is concentrated in the NH during the winter, thus increasing the interhemispheric temperature gradient from a zonal mean perspective. The interhemispheric temperature gradient is

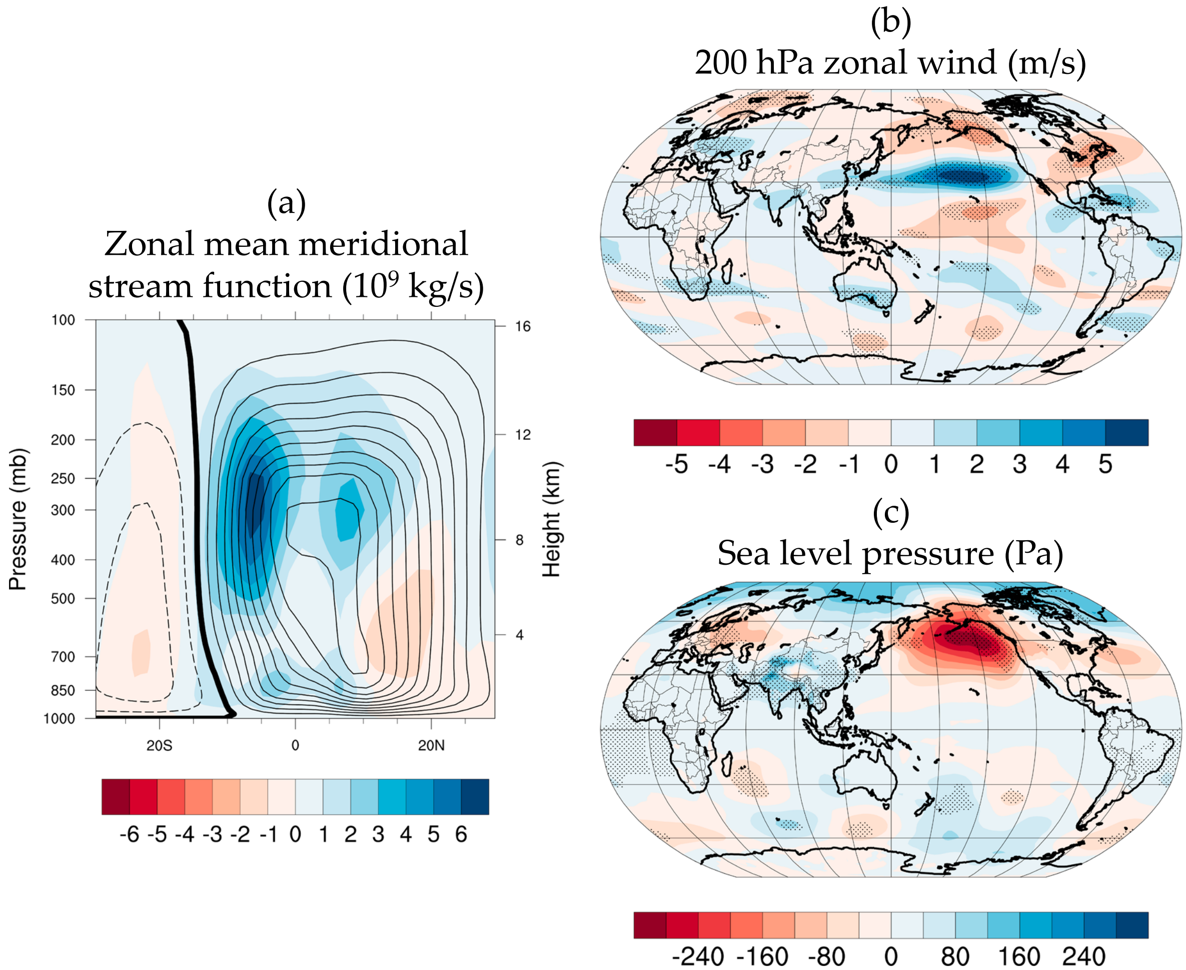

Figure 4. Simulated results of (a) zonal mean of the meridional stream function (shading: IRR-CTR, 10^9kg/s; contour: CTR, CI: 0.2×10^{11} kg/s, positive (negative) values are in solid (dashed) lines); (b) IRR-CTR 200 hPa zonal wind (m/s); and (c) IRR-CTR sea level pressure (Pa) (dotted: $p < 0.1$ for Figures 4b and 4c).

crucial for tropical rainfall and the Hadley circulation, and the concept has been employed in studies on paleoclimatic scenarios, present-day climatic variations, and anthropogenic aerosol forcings to assess the effects of interhemispheric asymmetric thermal forcing [e.g., *Chiang and Bitz*, 2005; *Broccoli et al.*, 2006; *Bollasina et al.*, 2011; *Lee et al.*, 2011b; *Chiang and Friedman*, 2012; *Swann et al.*, 2012; *Friedman et al.*, 2013; *Hwang et al.*, 2013]. A higher interhemispheric temperature gradient tends to transport more energy between the hemispheres.

The changes in the zonal mean meridional stream function between the CTR and IRR simulations (Figure 4a) show an intensification of the Hadley circulation in response to the boreal cooling induced by irrigation. The changes in the tropical circulation cause more angular momentum to be transported to the NH midlatitudes and result in an intensification of the subtropical jet [*Held and Hou*, 1980; *Lindzen and Hou*, 1988], centered over the northeastern Pacific Ocean (Figure 4b). Averaged from 150°E to 120°W, the 200 hPa zonal wind speed at 30°N has increased for 6.3%. Following the strengthening of the subtropical jet, there is anomalous westward wind velocity north to 45°N. The weakening of midlatitude westerlies is a manifestation of weakened transient eddy activity over North Pacific, which has been shown in observational and theoretical studies associated with a strengthened subtropical jet [e.g., *Nakamura*, 1992, 2002; *Lee and Kim*, 2003]. The resulting anomalous cyclonic circulation exhibits a barotropic structure and corresponds with a deepening and eastward shift of the semipermanent Aleutian low, as observed from sea level pressure differences (Figure 4c). The prevailing winter weather pattern or storm track is related to the position and strength of the jet stream, and these changes in the northeastern Pacific also resemble the positive PNA-like pattern and are consistent with the teleconnection pattern associated with the normal mode instability.

The potential influences of the interhemispheric thermal asymmetry (ITA) to remote climates have been studied using Paleoclimate Model Intercomparison Project Phase 2 models in which *Chiang and Fang* [2010] found notable differences in wintertime northeastern Pacific sea level pressure and Pacific jet stream intensity in mid-Holocene simulations. Compared with present-day simulations, *Chiang and Fang* [2010] found that the Aleutian low was deepened, the subtropical jet stream intensified near the northeastern Pacific, and the transient eddy activity reduced in the main storm-track region. The differences in the mean climatic states were attributed to a larger interhemispheric thermal gradient, which is due to stronger seasonality caused by precessional forcing. In association with a stronger seasonality, the monsoon intensity in the mid-Holocene was stronger than in the present day and the tropical rainfall was also changed. The results thus shared the same mechanism (ITA) as that in the current study.

We also calculate the ITA over Indian Ocean sector from both ERA-Interim and CCSM4 LM simulations to make composite analyses. The results indicated that the linkage between surface temperatures over Indian subcontinent and northeastern Pacific climate does exist (cooler South Asia and warmer Indian Ocean, deeper Aleutian low), which supports our findings from model simulations (for details please see SI).

4. Discussion and Conclusions

In the model experiment, the surface air temperature in the IGP region decreases by approximately 1°C from the CTR simulation to the IRR simulation. It is necessary to point out that surface temperature in IGP was projected to increase 4.5°C by the end of 21st century without considering the irrigation effect in the 8.5 W/m^2 representative concentration pathways 8.5 simulation of CESM. Also, as the projected future irrigation water demand under global climate change has an increasing trend [*Wada et al*., 2013], the projected terrestrial hydroclimate and monsoon can thus be different if the irrigation impacts are included.

In the current study, we addressed the critical effect of agricultural irrigation in Asian low latitudes on the winter climate. The control simulation, which did not consider irrigation, underestimates the latent heat flux over the intensively irrigated region of the IGP; by contrast, increased low cloud cover in the IRR simulation spread the original evaporative cooling (from excess ET) to the Indian subcontinent scale. The cooling over the Indian subcontinent makes a larger land-sea thermal contrast between the tropical Indian Ocean and the Indian subcontinent. The low-level northeasterly wind strengthens approximately 5% over the Indian subcontinent and west Arabian Sea. The upper level convergence over South Asia induces positive PNA-like teleconnection pattern and warming over continental North America. Also, the zonal mean Hadley circulation is enhanced in a cross-basin manner and the Pacific subtropical jet is intensified, which might affect wintertime storm tracking in the northeastern Pacific because of the hemispheric asymmetric distribution of the irrigation applied. The tropical-extratropical climatic interaction is established as the upper level jet stream system is modified in the NH, and the Aleutian low is deepened and shifts eastward, which is consistent with the PNA teleconnection pattern.

This study can also be viewed an example of how a comprehensive Earth system model responds to an interhemispheric thermal asymmetry in the boreal winter season. The adjustment to the forcing in the current study was accomplished through South Asian winter monsoon circulation. The zonal connection of the tropical Indian Ocean and Pacific Ocean is essential in inducing climatic modifications over the northeastern Pacific and North America. The results also imply a climatic hot spot in the South Asian regions. Because it involves an immense landmass facing the Indian Ocean and located at rather low latitude, modifications of land surface conditions in South Asia can have the potential to affect remote regions. The anthropogenic perturbation of climates is highly dynamic with time evolution, geographical distribution, and even cultural backgrounds. Therefore, to generate a climate simulation that is more realistic (particularly for future climate projections), it is crucial to understand in detail the South Asian land use and management such as the irrigation discussed in this study.

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