1. Introduction

The Hetao Irrigation District in western Inner Mongolia, China, is one of the most extensive irrigations in Asia (Fig. 1a). About 5x10^9 m^3/year of water is supplied by the Yellow River. The Hetao Irrigation District creates a clear contrast of land use between the irrigated area and the surrounding dry area (Fig. 1b), which induces a prominent heat contrast along the boundary. The contrast of land use often induces clouds and precipitation as pointed out in many studies (e.g., Avissar and Liu, 1996; Pielke, 2001).

By a statistical analysis of satellite images, Sato et al. (2007) revealed the distribution of the frequency of cloud-appearance around the Hetao Irrigation District during daytime in summer. Figure 2 shows the cloud frequency derived from Geostationary Meteorological Satellite 5 (GMS5), which is modified after Fig. 4 in Sato et al. (2007). The frequency of cloud formation is lower over the irrigated area than over the Langshan Mountains and the Loess Plateau whose elevations are higher than that of the irrigated district. The frequency is also lower than that over the Ulan Buh Desert which has an elevation nearly identical to that of the irrigated area.

The contrast of land use between the Hetao Irrigation District and the surrounding dry area may induce the mesoscale circulation and convective clouds, as speculated by Sato et al. (2007). The objective of this study is to reveal the impact of the Hetao Irrigation District on cloud
formation using a mesoscale numerical model.

We focus on 4 August 2005 when the typical cloud formation is observed (Sato et al., 2007). Figure 3 shows a true color snapshot over the Hetao Irrigation District 14:10 LST on 4 August 2005 obtained with the Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua satellite. Numerous clouds are evident around the Hetao Irrigation District, e.g., the Langshan Mountains, the Loess Plateau, and the Ulan Buh Desert. No clouds appear over the irrigated area.

2. Design of numerical experiments

Numerical experiments are conducted using a non-hydrostatic numerical model, Advanced Research Weather Research and Forecasting (WRF) modeling system Version 2.2. Two-way nested grid systems are adopted. The coarse and fine grid systems have grid intervals of 15km and 3km, respectively. The domains of this simulation are shown as two black solid-line boxes in Fig. 1. WRF Single Moment 6-class graupel microphysics scheme is used in both domains. Land surface, surface-layer and boundary-layer processes are represented by the Noah land surface model, the Monin-Obukhov (Janjic Eta) scheme, and the Mellor-Yamada-Janjic (Eta) TKE scheme, respectively. The initial and lateral boundary conditions for the coarse grid system are interpolated from the 6-hourly NCEP global tropospheric analyses data (1x1 degree grids, 24 vertical levels). The simulations were executed from 00 UTC 1 August and integrated for 4 days.

Two experiments are conducted. One experiment is the SFC-WET run assuming a simplified irrigated area (hereafter, irrigated area) over the Hetao Irrigation District (Green area in Fig. 4a). The volumetric soil water content (hereafter, soil water content) is artificially kept at 0.4 in all soil layers within the irrigated area throughout the simulation, which corresponds to about 85% of the saturated soil water content there. The SFC-WET run simulates a small sensible heat flux and a large latent heat flux over the Hetao Irrigation District. Besides the irrigated area, the soil water content derived from the NCEP global tropospheric analyses data is adopted as an initial value, and then the soil water content is predicted every time step by the Noah-LSM scheme. Predicted soil water content is in the range between 0.1 and 0.25 on 4 August 2005 in the outer region of the irrigated area.

Another experiment is the SFC-DRY run not assuming the irrigation over the Hetao Irrigation District. The vegetation parameter of “Barren or sparsely vegetated” was applied to the Hetao Irrigated district. The initial soil water content was assumed to be the NCEP soil water content which is too coarse to resolve the Hetao Irrigation District. The soil water content was predicted by the Noah-LSM scheme, which does not include the physical process of irrigation. The SFC-DRY run simulated the large sensible heat flux and the small latent heat flux, which indicates that a dry surface condition is simulated as well as the surrounding dry area.

4. Simulation results

Figures 4a and 4b show the distributions of cloud water simulated by the SFC-WET run and the SFC-DRY run at 14 LST on 4 August 2005, respectively. A white color indicates simulated clouds, where the vertical integrated solid and liquid cloud water content exceeds 0.05 kg/m².

The SFC-WET run simulates clouds over the Langshan Mountains and the northern part of the Loess Plateau. Clouds also appear around the edge of the Ulan Buh Desert. Almost no clouds are generated over the irrigated area. The distribution of clouds is quite similar to the observation (Fig. 3). In contrast, the SFC-DRY run simulates clouds not only over the Langshan Mountains but also over the Hetao Irrigation District.

Fig. 4 Distributions of clouds at 14 LST (left) and surface temperature at 12 LST (right) simulated by the SFC-WET (top) and SFC-DRY (bottom) on 4 Aug. 2005. The green area in Fig. 4a shows the irrigated area. The surface temperatures are shown on 12 LST when almost no clouds are generated over the irrigated area. (Modified after Kawase et al. (2008))
Figures 4c and 4d show the land surface temperatures at 12 LST on 4 August 2005 simulated by the SFC-WET run and the SFC-DRY run, respectively. The low surface temperature over the mountains corresponds to the decrease of solar radiation by clouds and the cooling by rainfall at 12 LST. A clear contrast of the surface temperature is found between the irrigated area and the surrounding dry area in the SFC-WET run (Fig. 4c). The surface temperature in the irrigated area is about 15 K lower than that in the surrounding dry area. In the SFC-DRY run, the contrast of the surface temperature is quite small (Fig. 4d). These results suggest that the contrast of the surface temperature can affect cloud formation around the irrigated area.

The clouds near the boundary between the Hetao Irrigation District and Ulan Buh Desert in the flat lowland observed by the satellite (Fig. 3) are only simulated by the SFC-WET run. Figure 5 illustrates vertical cross sections of wind velocity along the SW-NE section in Figs. 4a and 4b. A simple moving average is taken for horizontal five grids so that a mesoscale circulation is emphasized by eliminating some noises caused by small-scale convections in the atmosphere.

Figure 5. Vertical cross sections of wind velocity and water vapor mixing ratio along SW-NE in Figure 4a at 14 LST. (a) SFC-WET and (b) SFC-DRY. The shadings show the level of water vapor mixing ratio. The light-gray indicates topography. The dark-gray shows that the averaged grids include parts of the irrigated area. (cited from Kawase et al. (2008))

In the SFC-WET run, the southwestern component of wind is predominant over the southwestern dry area, while the northeastern component of wind is predominant over the northeastern irrigated area at the layers below 1,500 m (Fig. 5a). Above 2,000 m, the southwestern component of wind is predominant over the whole area. The two different winds at the lower level cause the convergence over the boundary between the dry area and irrigated area. Prominent upward and downward flows are found over the dry area and the irrigated area, respectively. Therefore the SFC-WET run simulates a clear mesoscale circulation between the dry area and the irrigated area.

On the other hand, no significant circulations are simulated in the SFC-DRY run (Fig. 5b). The southwestern component of wind is predominant in the entire layer. In consideration of the large southwestern component of wind in the SFC-DRY run, the northeastern component is relatively large over the irrigated area in the SFC-WET run (Fig. 5a).

5. Discussion

The numerical experiments also suggest other impacts of irrigation on cloud distribution. Numerous clouds are simulated over the Langshan Mountains in both the SFC-WET and SFC-DRY runs, while only the SFC-WET run simulated the cloud formation over the northern Loess Plateau and the cloudless irrigated area.

The mechanisms of the cloud generation and inhibition around the Hetao Irrigation District are considered in terms of mesoscale circulations. From 10 LST, a mesoscale circulation (hereafter, northern circulation) develops between the Hetao irrigation area and the Langshan Mountains in both the SFC-WET and SFC-DRY runs (Fig. 6a). A few hours after the generation of the northern circulation, the SFC-WET run also simulates the development of a circulation between the Hetao Irrigation District and the northern Loess Plateau (hereafter, southern circulation) (Fig. 6b). The circulation cannot be simulated in the SFC-DRY run. It is suggested that the northern and southern circulations produce clouds over the Langshan Mountains and the northern Loess Plateau, respectively (Fig. 3a).

Lee and Kimura [2001] reported that a mountain-valley circulation develops earlier than a land-use-induced circulation. The northern circulation develops in the morning in both the SFC-WET and SFC-DRY runs, which indicates

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that the circulation has the characteristics of the mountain-valley circulation. On the other hand, the southern circulation develops in the early afternoon only in the SFC-WET run, which indicates that the circulation is ascribed to the land-use-induced circulation as well as the circulation between the Hetao Irrigation District and the Ulan Buh Desert.

Figure 6. Vertical-latitude cross section of zonal mean vertical wind from 107.5E to 108.5E simulated by SFC-WET run (left) and SFC-DRY run (right) at 10 LT (top) and 12LT (bottom) on 4 August 2005. Green area is the irrigated area.

The northern circulation is, however, assumed to be induced by not only the difference of altitude but also the difference of land use, because the circulation is stronger in the SFC-WET run than that in the SFC-DRY run. The mountain-valley circulation can be enhanced by the heat contrast between the irrigation area and the mountain area. The downward flow can suppress the cloud generation over the Hetao Irrigation District, especially in the early afternoon when both the land-use-induced and mountain-valley circulations are developed well.

Figure 7 and b show true color snapshots at 13:45 LST on 20 and at 13:45 LST on 13 May 2005 observed by the MODIS/AQUA.

6. Conclusion

A numerical experiment assuming a simplified irrigation simulates the cloud formation around the Hetao Irrigation District using realistic atmospheric conditions and topography. The low surface temperature on the Hetao Irrigation District produces a wind that blows toward the Ulan Buh Desert, where the surface temperature is high, and results in the land-use-induced circulation at the lower layer. The experiments also suggest that the downward flow can inhibit the cloud generation over the Hetao Irrigation District in the afternoon, when both the land-use-induced circulation and mountain-valley circulation are well developed.

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