Impact of change in land surface condition on the development of the atmospheric boundary layer and cumulus clouds over the Loess Plateau in China
—Numerical experiment—

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1. Introduction

A characteristic topographical terrain spreads over the southern part of the Loess Plateau in China. The plateau consists of flat tableland at the top of the plateau and steep gullies distributed with high complexity. No-irrigated agriculture has been conducted on the flat tableland. Large area was covered by fields of wheat, maize, and apple. Precipitation is significantly important to maintain agriculture in the plateau.

Most of annual precipitation occurs in five months from May to September (Owada et al., 2005). Cumulus clouds generated frequently during these period. Cumulus clouds that developed to a high altitude in the afternoon were observed in late of June in 2005 and 2006 (Takahashi et al, 2007). In such cases, cumulus convection is likely to enhance entrainment at the top of the atmospheric boundary layer (ABL) (Nishikawa et al, 2007). Strong vertical wind that occurs interactively in the ABL and cumulus clouds might enhance the vertical transport of water vapor between the ABL and free atmosphere (Takahashi et al., 2007).

Intense precipitation tends to occur in the evening in the plateau. Such precipitation is considered to be related to development of convective activity in daytime. Topography and wetness of land surface can influence generation of cumulus cloud in addition to the atmospheric conditions such as wind field, air temperature, and humidity. This study aims to investigate the sensitivity of ABL development and cloud activity to the land surface conditions over the Loess Plateau. Numerical experiments were conducted in order to clarify the extent of influence of the land surface wetness to generation of cumulus cloud over the ABL. The land surface was treated as a completely flat and homogeneous terrain in order to exclude any topological effects in this study.

2. Model description

CReSS (Cloud Resolving Storm Simulator) (Tsuboki and Sakakibara, 2001) was used for our numerical experiment in this study. Table 1 shows the initial and boundary conditions, parameters, and some physical schemes adopted in CReSS in this study. The model domain is the area of 20 km × 20 km with 12,824 m depth in the vertical domain in this numerical experiment. The Changwu Agro-Ecological Experimental Station is located at the center of the domain. The model domain contains 200 grid points in each horizontal direction and 120 layers in the vertical direction that is stretched according to the function of hyperbolic tangent for the layers above a height of 4.2 km. The boundary conditions of shortwave radiation and the initial profiles of air temperature, humidity, and wind velocity were input as the meteorological conditions observed on 19 June 2005, when strong vertical winds were observed in the afternoon. The time domain of the simulations was set to daytime from 8:00 local standard time (LST) to 18:00 LST with time step of 1 second.

We conducted numerical experiments under several conditions, i.e. changing the evaporation efficiency β at the land surface and the vertical profiles of relative humidity (RH) in the atmosphere. (β, RH) of each experiment are Exp. 1: (0.05, obs), Exp. 2: (0.05, obs+5%), Exp. 3: (0.2, obs), and Exp. 4: (0.2, obs+5%). Here, 'obs' means the observed profile of RH. The conditions of $\beta = 0.05$ and 0.2 correspond to dry and wet surface conditions, respectively.

3. Results and discussion

Figure 1 shows the horizontal distributions of wind velocity at heights of 1.2 km and 2.5 km in the case of Exp. 1 and Exp. 3. Colors mean the vertical wind velocity. Vectors mean horizontal wind vectors. Under the condition of dry land surface ($\beta = 0.05$), strong upwind appeared at a height of 2.5 km, while the vertical wind velocity was weak at the same height under condition of wet land surface ($\beta = 0.2$). This is due to the fact that the ABL was enhanced by much amount of sensible heat from the land surface to the atmosphere in the case of $\beta = 0.05$. The ABL developed to height of about 3 km, where strong upwind reached around there. Organized structures consisting of convective cells developed and generated upward wind as shown in Fig. 1(b) and (d).

Figure 2 shows time-height sections of the vertical wind velocity and specific humidity for each case of the experiment. We can see that the ABL developed relatively rapidly to higher altitudes with strong vertical winds in the case of $\beta = 0.05$. The influences of RH on development of the ABL were relatively small in both cases of $\beta = 0.05$ and $\beta = 0.2$.

Figure 3 shows time-height sections of specific humidity and the cloud liquid water content for each case of the experiment. Increase of RH by 5% caused increase in emergence of cloud liquid water in both cases of $\beta = 0.05$ and $\beta = 0.2$. This means that the slight increase of RH can stimulate generation of cumulus cloud, especially in the case of wet surface conditions, $\beta = 0.2$, in which supply of water vapor from the land surface is larger than dry surface conditions, $\beta = 0.05$.

Precipitation that reaches to the ground surface did not occur in all of the cases of the experiments in this study. However, we could confirm that generation of cumulus cloud is sensitive to vivid increase of relative humidity. Therefore, advection of convective activity would enhance generation of active cloud convection that can produce precipitation. In the observation on 19 June 2005, precipitation occurred in the evening on that day. At that time, the convective activity might be stimulated by the ABL then developed over the plateau.

4. Conclusions

This study conducted numerical experiments using cloud-resolving model for the purposes to clarify the factors that influence effectively the generation of cumulus cloud over the Loess Plateau in China. Especially, this study focused on the influence of the land surface wetness to generation of cumulus cloud. Thus, completely flat and homogeneous land surface was assumed in order to avoid any topological effects on generation of cumulus cloud. The meteorological conditions on 19 June 2005 were used in the experiments, since strong vertical winds were observed in the ABL especially in the afternoon.

The obtained results are summarized as follows. Under the condition of dry land surface, strong upwind developed especially and reached to a height of about 3 km. On the other hand, under wet surface condition, the development of the ABL and the vertical wind velocity in the ABL were relatively weaker than those under dry surface condition. Organized structures of convective cells developed. In both of the cases of dry and wet surface conditions, circular upwind areas developed at the edge of each cell. Such structure developed stronger under dry surface condition. If the vertical profile of relative humidity increases by 5%, generation of cumulus cloud was activated in both of the cases of dry and wet surface conditions. Especially, enhancement of generation of cumulus cloud was more prominent under wet surface condition.

Further study will be needed to clarify the mechanism of the interaction between the ABL and the active cloud convections in synoptic scale that have potential to cause precipitation, in order to understand the land-atmosphere interaction and the water circulation in the Yellow River basin.

Table 1. Boundary conditions, parameters, and various physical schemes in CReSS used in this study

Model	Cloud Resolving Storm Simulator (CReSS) version 2.1
Turbulence scheme	1.5 order closure scheme
Cloud physics	Warm rain
Land surface flux	Bulk method
Soil layers	0.1 m×30 layes
Radiation	Energy budget at land surface
Model domain	Horizontal 200×200 (20 km×20 km)
	Vertical 120 layers (12824.0 m)
Resolution	Horizontal 100 m
	Vertical 50 m (Stretching by function (tanh) above 4.2 km)
Time-step	1 second, Totally 36000 seconds (10hours)
Lateral condition	Periodic condition
Upper boundary	Non-slip condition
Lower boundary	flat surface (1224 m a.s.l.)
Forcing	Diurnal variation of shortwave radiation
Initial condition	Lower layer: Microwave radiometer and wind profiler radar
	Upper layer: radiosonde data 00Z (8BST) at Pingliang
Albedo	0.156
Evaporation efficiency	0.05, 0.2
Surface roughness	0.47 m
Temperature at bottom soil	293.0 K
Soil heat capacity	2.3×10^{6} J m^{-3} K^{-1}
Thermal diffusivity of soil	7.0×10^{-7} m^{2} s^{-1}

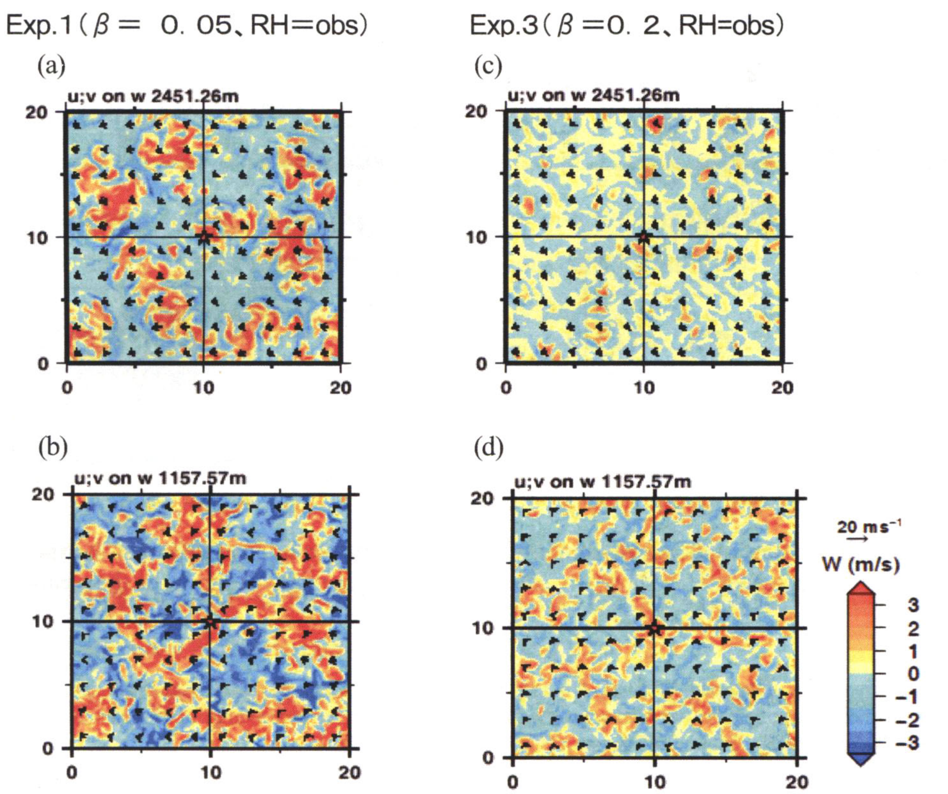

Fig. 1. Horizontal sections of wind velocity for Exp. 1 and Exp. 3. The vertical velocities are shown by colors. The horizontal wind velocities are shown by the vectors. The upper figures are wind velocities at a height of about 2.5 km and the lower figures are those at a height of about 1.2 km.

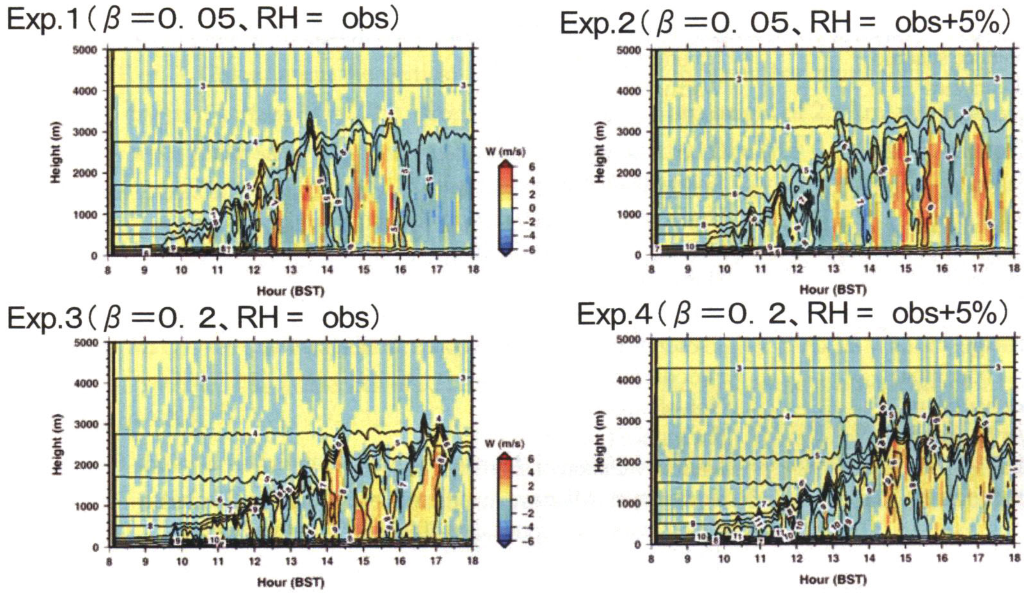

Fig. 2. Time-height sections of the vertical wind velocities and specific humidity in each experiment. The vertical wind velocities are shown by the colors and specific humidity is shown by the contour.

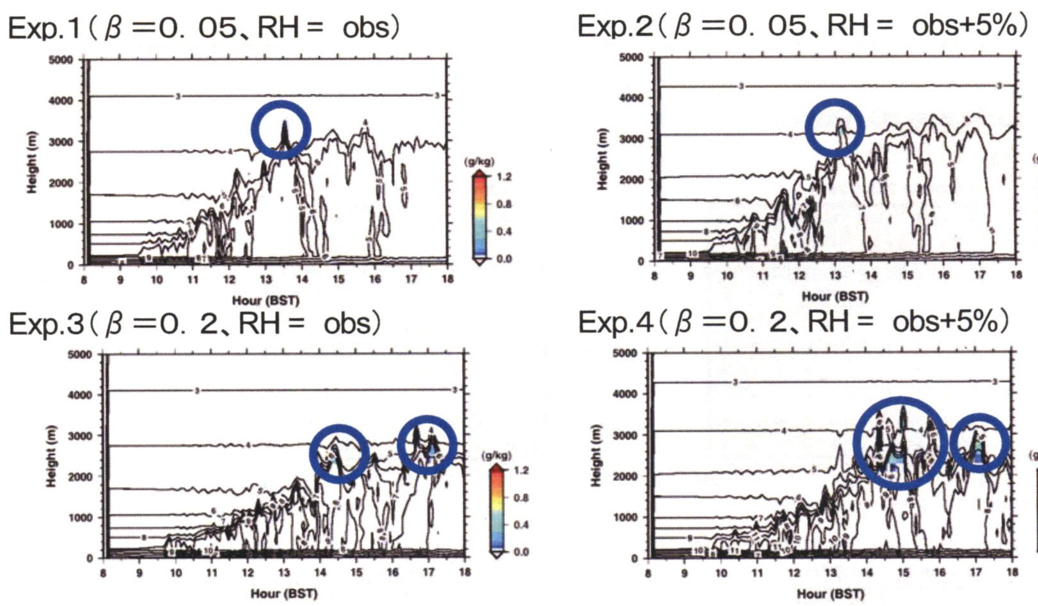

Fig. 3. Time-height sections of the cloud liquid water content and specific humidity in each experiment. The cloud liquid water contents are shown by colors and specific humidity is shown by the contour.

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