The impact of diabatic heating over the Tibetan plateau upon northeastern Asia arid region

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Abstract

Formation mechanism of arid climate over northern China is investigated by a series of numerical experiments. On that region summertime precipitation is strongly reduced by a regional scale subsidence. Sensitivity experiment without condensation process is conducted in order to clarify the physical mechanism for the generation of the subsidence. Simulated vertical velocity shows the descent at middle troposphere over the arid region. On the other hand ascending motion appears immediate above the Tibetan plateau because the planetary boundary layer acts as an elevated heat source over the plateau. However, only gentle vertical motion is left in the case when diabatic processes is turned off in the model. That implies mechanically forced subsidence by the terrain, such as mountain wave, is not enough to cause the subsidence. To the contrary, thermal effect of the plateau is fairly larger since the subsidence over arid region is enhanced when diabatic heating is artificially given only over the plateau. Northward propagation of the stationary Rossby wave is inferred to cause the robust subsidence over the arid region in northern China. The stationary Rossby wave tends to propagate northward because subtropical westerly jet is being situated north of the plateau in boreal summer. Therefore, the stationary descending motion prevails over northeastern Asia, which consequently reduces the precipitation around arid region. We also confirmed that the stationary Rossby wave is likely to propagate not only northward but also southward of the plateau when zonal mean of January is assumed as a boundary condition. Spatial relationship between the plateau and the westerly jet undergoes transition period from spring to summer. The relationship could widely affect the seasonal evolution among Asian region since the spatial distribution of the subsidence will be changed simultaneously around the plateau.

Keyword: arid climate, northeast Asia, regional climate model

1. Introduction

Broadly spread arid climate covers northern China, for example the Taklimakan and Gobi desert. They can be regarded as part of subtropical arid climate in Eurasian continent extending from Arabian Peninsula, Central Asia, northern China, and Mongolia. Subtropical anticyclones related with the subsidence branches of Hadley circulation generally extend up to 30 degrees in both hemispheres. Thus, its remarkably higher latitude is one of the major interesting issue involving with Eurasian continental desert.

Previous studies with Global Circulation Models (GCMs) have shown that more precipitation is supplied even in these continental deserts if any orography is absent (Manabe and Terpstra, 1974); that is, the distance from the ocean is not a sufficient reason for the continental interior desert. Otherwise, the influences of orography should be more important and need to be discussed for the case of Taklimakan and Gobi desert because they are situated along northern periphery of the Tibetan plateau.

Broccoli and Manabe (1992) have stated that the large scale orography contributes to the winter dryness by the results of a GCM experiment. They have suggested that the plateau causes a stationary ridge of subtropical westerly over northeastern Asia, which makes synoptic disturbances less active. During summer, however, heating contrasts over the Asian monsoon region widely modify the atmospheric circulation, and forms quite different system from that in wintertime. During summer, large amount of precipitation occurs over the Bay of Bengal, southeast Asia, and ITCZ regions. Also heavy precipitation is observed in the regions of eastern China, Korea, and Japan. On the other hand, arid climate is found in central Asia around the Caspian Sea, where summer subtropical anticyclone is remotely enhanced by a huge amount of diabatic heating in south and southeast Asia (Rodwell and Hoskins, 1996). Moderate precipitation is observed in Mongolia and Far East Siberia. More than half of annual precipitation occurs during summertime in these regions. However, arid region is locally present corresponding to Taklimakan and Gobi desert. We aim to clarify the formation mechanism of this arid climate by series of numerical experiments using a regional climate model (RCM).

2. Numerical experiments

The RCMs are often used for the process studies of regional climate system (e.g. Yoshikane and Kimura, 2003). The advantages of RCM are the higher spatial resolution and an ability to carry out the idealized sensitivity studies. The modified version of RAMS (regional atmospheric modeling system), TERC-RAMS (Sato and Kimura, 2004) is adopted in this study. Horizontal resolution of the model is 150 km, and the model domain covers almost whole Asia and Siberia. The model atmosphere is divided into 30 layers with the finest resolution of 110 m at lowest level, stretching up to 900 m in upper layers. Precipitation is calculated using both microphysics and cumulus parameterizations. In a zonal mean experiment, referred to as ZM, lateral boundary conditions are nudged by a global zonal mean values during July of 2000 calculated using the reanalysis data. Since boundary variables are stationary during the numerical integration, we can neglect the synoptic disturbances passing through into the model boundary. According to this, the circulation induced by surface inhomogeneity, i.e., orography and ocean-land contrast, and zonal flow itself becomes the most dominant factor controlling a climate system in the ZM experiment.

Condensation process plays an important role on atmospheric circulation during warm season, because it widely modifies the energy balance as a result of change in water phase. The sensitivity of the latent heat release is examined in an experiment (referred to as NoC) by turning off the condensation process in the model without any other changes from the ZM experiment.

The Tibetan plateau may still act as an elevated heat source even if no condensation occurs in the NoC experiment, because the plateau is directly heated by the solar radiation. Another sensitivity experiment (referred to as NoR), which is same as NoC but excludes the radiation process, is carried out in order to simulate only mechanically forced flow passing over and around mountain like Rossby waves and mountain waves. All sensitivity experiments are carried out during 30 days, and the averaged values during only last 10 days are analyzed.

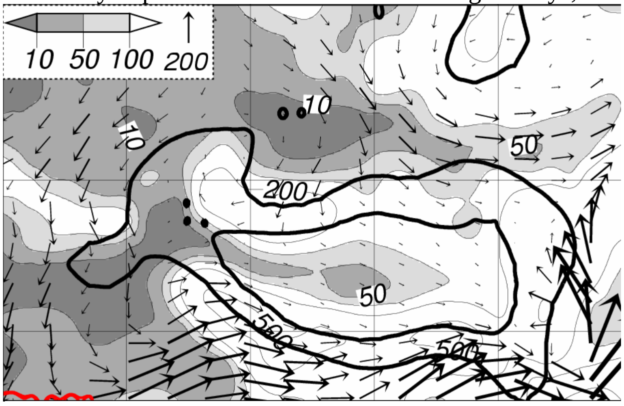

Figure 1: Average precipitation (mm/month) and vertically integrated water vapor transport (kg/m/sec) in ZM experiment.

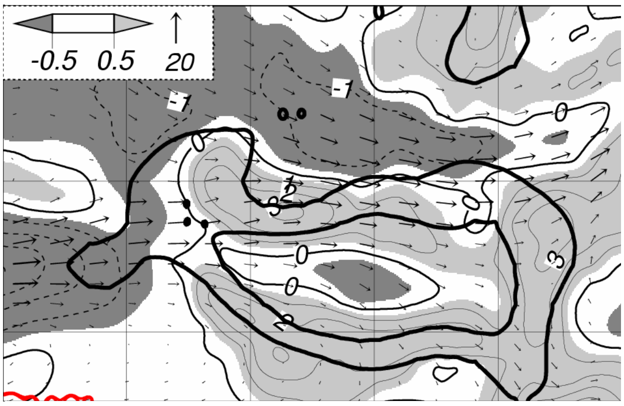

Figure 2: Averaged vertical motion (cm/sec) and wind (m/sec) at 400 hPa in ZM experiment.

3 Result

3.1 ZM experiment

Figure 1 shows 10-days averaged precipitation and water vapor flux by the ZM experiment. The features of rainfall distribution are simulated well, and aridity in northern China appears even in this sensitivity experiment. Rainfall amount around northeastern Asia arid region is less than 10 mm/month. The simulated rainfall distribution indicates that the interaction between zonal mean components and the surface boundary conditions, such as topography, is essential for the formation of the arid are in northern China.

Figure 2 illustrates the vertical velocity (shaded) and horizontal wind at the level of 400 hPa. Velocity of the westerly has a maximum around 43N over eastern Asia. Distinct descending motion is simulated over central Asia being correspond to the aridity around the Caspian Sea. Another robust descent motion stronger than 1.0 cm sec^{-1} appears on just north of the plateau extending from 81E to 98E. In comparison with precipitation of this run (Fig. 1), it is apparent that each dry region completely corresponds to the subsidence at this level. On the other hand, upward velocity is strong around Southeast Asia, Kunlun Mountain, and northeast China. These regions are almost equal to the region of heavy rainfall. In next section, we continue to investigate how the descending motion is formed over the arid region, since it is apparent that the subsidence strongly reduces the precipitation in this area.

3.2 NoC and NoR experiments

The vertical motion and horizontal wind at 400 hPa in the NoC experiment is shown in Fig. 3. Ascending motion is not so evident over southeast and south Asia regions since convection process is turned off in this sensitivity experiment. Figure 3, however, shows that the steady upward motion is generated over the Tibetan plateau in case without condensation process. A robust descending motion, which is greater than 2 cm sec^{-1} in magnitude, also appears over the desert region. Since the level of 400 hPa almost corresponds to the mean height of the planetary boundary layer over the plateau. The upward

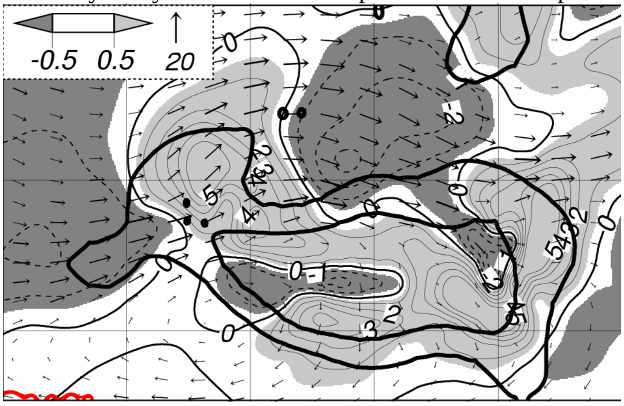

Figure 3: Same with Fig.2 but for NoC experiment.

motion should be mainly driven by the sensible heat flux caused by the radiative heating on the plateau surface. This means the heating process which may induce the subsidence over the arid region is not always necessary to be condensation heating associated with cumulus convection.

Figure 4 illustrates the vertical motion and horizontal wind at 400 hPa in the NoR experiment. Only very gentle upward and downward motions are recognized over west and east sides of the plateau, respectively. Nevertheless, the amplitudes of the vertical motions are about ten times smaller than those simulated by the run with the radiative heating (Fig. 3). Therefore, the mechanical influence is expected to be quite small for the vertical motion during summer, when subtropical westerlies are relatively weak, while it contributes largely in winter dryness (Broccoli and Manabe, 1992). Solar radiative heating, instead, plays an important role on the intensification of both upward and downward motion around the plateau. The relationship between the positions of heat source and the downward motion will be discussed in next section.

4 Discussion

4.1 Elevated heat source

Since Tibetan plateau is elevated about 4500 m above sea level, its mean planetary boundary layer may extend to the middle troposphere. Solar heating on such an elevated surface should widely affect the atmospheric circulation.

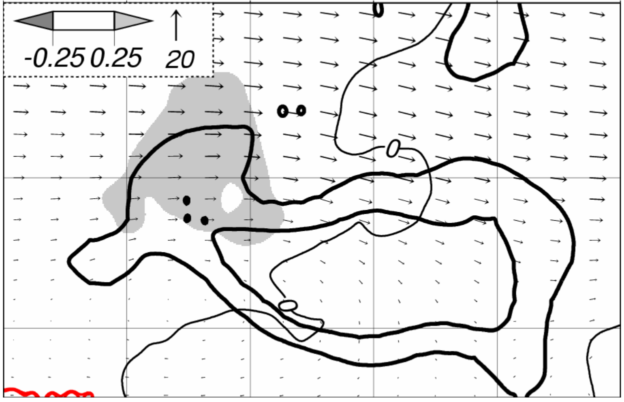

Figure 4: Same with Fig.2 but for NoR experiment.

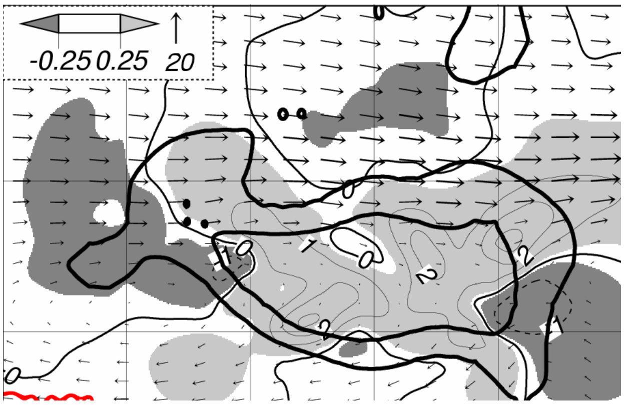

Figure 5: Same with Fig.2 but for TbQ experiment.

We now conduct a TbQ experiment in which artificial heat source is given on NoR experiment. The heat source is placed only over the Tibetan plateau where ground altitude exceeds 3000 m ASL. Although vertically integrated diabatic heating rate depends on ground altitude, it is approximately 160 W m^{-2} over the Plateau. The heat source is distributed between ground surface and about 6500 m ASL. In Fig.5 vertical motion and horizontal wind at 400 hPa are shown. Artificial heating causes upward motion over the plateau, while downward motion prevails over the northern side of the plateau. The downward velocity is about -0.3 cm sec^{-1}. Subsidence in Great Indian Desert is also seen. The horizontal distribution of vertical motion is close to that in the ZM or NoC experiment (see also Fig.2, Fig.3). Figure 5 indicates that the heating over the plateau does cause the subsidence which reduces the precipitation over the desert region.

The subsidence tends to be stronger when lower layer is heated strongly in case that the total energy of the heating is fixed. This indicates that the sensible heating associated with daytime mixed layer could be more efficient to cause the subsidence than the condensation heating by the cloud physics in upper layer.

4.2 Response to the heat source

The amount of diabatic heating estimated from reanalysis data is larger in tropical regions, around the Bay of Bengal and Southeast Asia, than that over Tibetan plateau. We, therefore, attempted another experiment by placing the heat source over South Asia instead of the plateau. The experiment shows that the prevailing subsidence appears only over Central Asia (not shown), which is consistent with previous studies (Broccoli and Manabe, 1992; Rodwell and Hoskins, 1996). This means that the huge amount of diabatic heating over south and southeast Asia region does not directly affect the subsidence over desert region in northern China.

Figure 6 shows the global zonal mean of zonal wind velocity at 200 hPa.. In upper troposphere subtropical westerly jet retreats poleward during summer. It runs completely north of the Tibetan plateau from June to September when diabatic heating over the plateau becomes much stronger. As mentioned by Hoskins (1996), the mid-latitude subsidence is likely to be accelerated according to the interaction between Rossby wave and subtropical westerly jet.

We performed very simplified experiments using TERC-RAMS, in which topography is assumed to be flat and that surface is covered by land. The rectangular shaped heat source is added around 35N,100E. Zonal mean fields of July, January and April are calculated from NCEP/NCAR reanalysis to use as a boundary condition of numerical experiments in order to investigate the difference of atmospheric response to the heat source. Figure 7 illustrate the typical propagation pattern simulated by the simplified experiments. In Fig. 7b, robust subsidence is formed in west and north of the heat source,

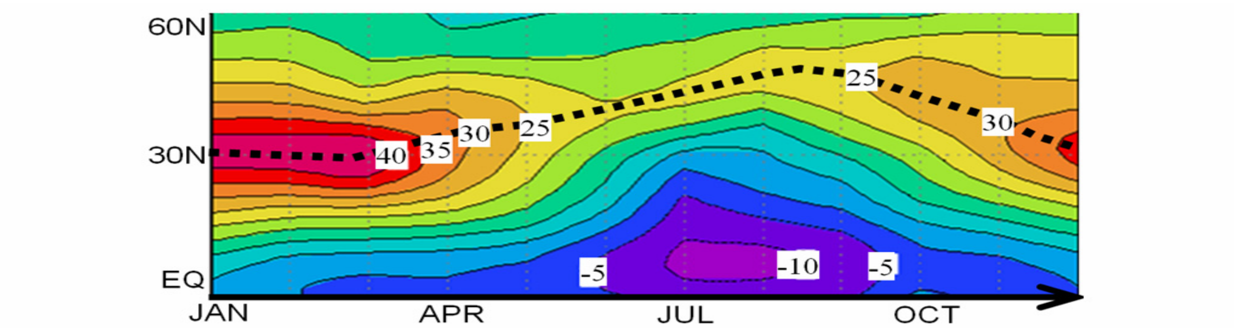

Figure 6: Global zonal mean of zonal wind velocity (m/sec)

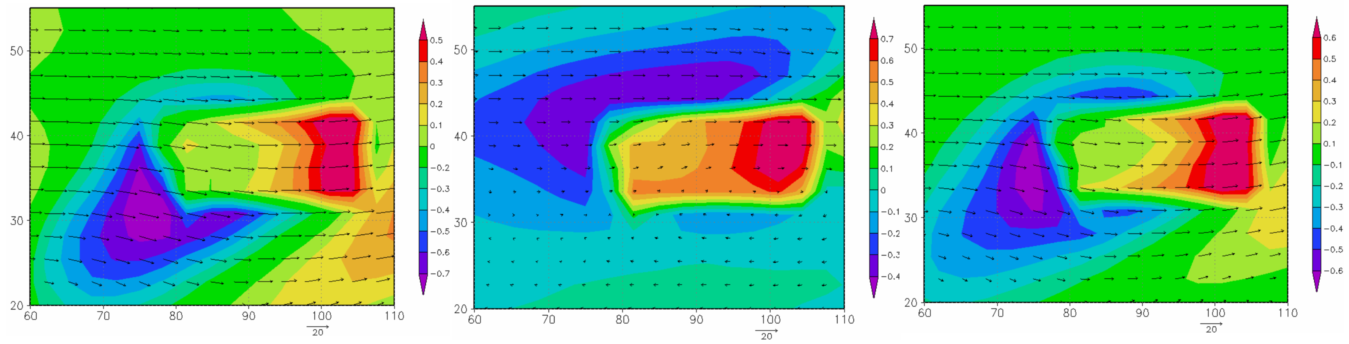

Figure 7: Vertical wind velocity (m/sec) and wind vectors at 500 hPa responded by rectangular heat source. Zonal mean of (a) January, (b) July, (c) April is used for lateral boundary condition.

which shows that the diabatic heating over the plateau will cause subsidence over northern China during summer. The result is consistent with our sensitivity experiments shown in Fig. 3 and Fig. 4, although the results are so clear due to many assumptions for simplicity. On the other hand, propagation to the south is obvious during winter (Fig. 7a) because subtropical jet situates in south of the heat source. This means that the descending motion may prevail in winter in the vicinity of the plateau over south and southeast Asia. Before middle summer, the subtropical jet shifts poleward from south to north of the Tibetan plateau. Thus, the response directions to the heat source extend both south and north of the plateau. These results indicate that the direction of the Rossby wave propagation strongly depends on the meridional location of westerly jet. Since the location of the westerly jet varies with a season, the horizontal distributions of the subsidence become quite different from spring to summer, which could affect widely the seasonal evolution of the Asia and Indian monsoon.

5 Summary

The reason of summertime aridity over northeastern Asia is investigated by RCM experiments. Over desert area, robust descending motion, which reduces the precipitation, prevails in the control experiment with diabatic heating process. However, the descending motion tends to be very weak when diabatic process is turned off in the model. Solar radiative heating on the Tibetan plateau leads to a generation of Rossby wave. The stationary Rossby wave tends to propagate northward because subtropical westerly jet is being situated north of the plateau in boreal summer. Therefore, the stationary descending motion prevails over northeastern Asia, which consequently reduces the precipitation around arid region. Diabatic heating over tropical region does not affect directly over the desert since the position of subtropical westerly is not favorable for northward propagation of Rossby wave.

Acknowledgement

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