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Effect of Orography on Land and Ocean Surface Temperature

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INTRODUCTION

Large-scale mountains such as the Tibetan plateau play an important role in making global climate system through dynamical and thermodynamical effects. Most of previous model studies are conducted by atmospheric general circulation models, and focused on climate over land. However mountain uplifts not only change land surface temperatures but can also affect sea surface temperatures (SST). Kitoh (1997) showed by using a coupled atmosphere-mixed layer ocean model that the global mean SST dropped 1.4 K with a mountain uplift, mainly due to increased low-level clouds over the subtropical eastern oceans. The increased frequency of low-level clouds is related to subtropical anticyclones intensified by a strong temperature contrast between the continent and the ocean. The land surface temperature drops due to the "lapse-rate effect". When this effect is eliminated, the continent interior becomes warmer with the mountain uplift because clouds become fewer and the surface drier due to decreased moisture transport. Southern Asia has become cooler because monsoon-induced precipitation wets the ground and increases clouds.

We revisit this problem using a global coupled atmosphere-ocean general circulation model, and investigate the effects of orography in the context of the atmosphere-ocean-land system. Here we address the following questions: how the orography affects the ocean circulation and what is the effect of incorporating the ocean general circulation on the surface temperature changes?

MODEL AND EXPERIMENT

A global coupled atmosphere-ocean general circulation model (MRI CGCM1, Tokioka *et al.*, 1995) is used for this simulation. The atmospheric part of the model has horizontal resolution of 4° latitude by 5° longitude, and 15 vertical levels with the model top at 1 hPa. The oceanic part adopted a variable resolution of 0.5°–2.0° for the latitudinal direction with finer grid in the tropics and a fixed 2.5° for the longitudinal direction. There are 21 vertical levels with the bottom at a depth of 5000 m. A realistic sea ice model is included. Seasonal and diurnal cycles are included in the model integration. The model uses flux adjustments for heat and fresh water. The model was integrated for 30 model years with a realistic land-sea distribution and orography (M run) and with a flat surface everywhere

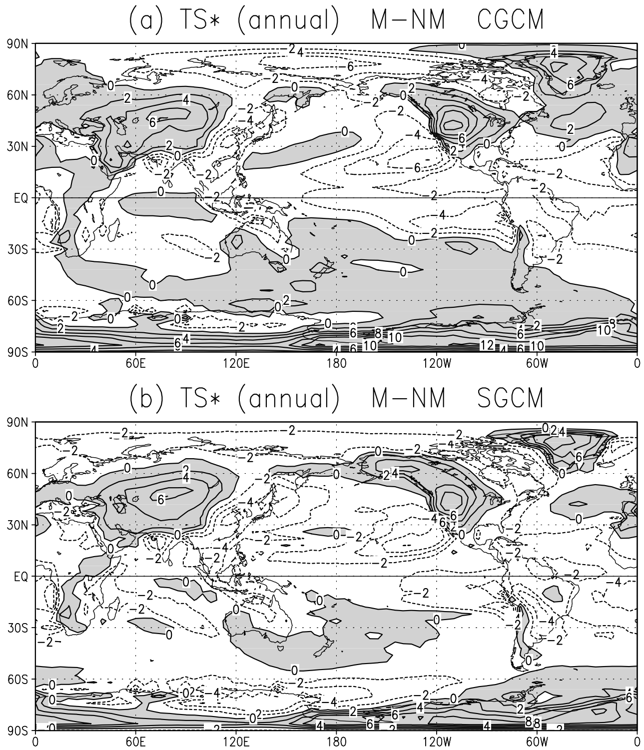


Fig. 1. Annually averaged difference (M-NM) in surface air temperature of (a) CGCM and (b) SGCM. Lapse rate effect due to orography is adjusted by 6.5 K km^{-1}, the environmental lapse rate. The contour interval is 2 K.

by keeping the same land-sea distribution (NM run). Elevation of the highest point over Tibet is 4400 m in M. Averages are taken from the last 10 years of integration when the global mean SST and sea ice are near equilibrium. This set of experiments is called the CGCM run.

In the second set of experiments we use the atmosphere/mixed layer ocean-coupled model (SGCM) where the oceanic model is replaced by a constant 50-m depth slab ocean. The model was integrated for 12 model years and the last 5 years of data were used. Results of this SGCM run are described by Kitoh (1997).

SURFACE TEMPERATURE CHANGES BY OROGRAPHY

As the temperature decreases with elevation, temperature in the mountainous regions become lower owing to the “lapse-rate effect.” Therefore, the surface temperature changes are adjusted by assuming a typical environmental lapse rate of 6.5 K km^{-1} in comparing the result of M run with the one of NM run. Figures 1(a) and (b) show the difference in the annual mean surface air temperature

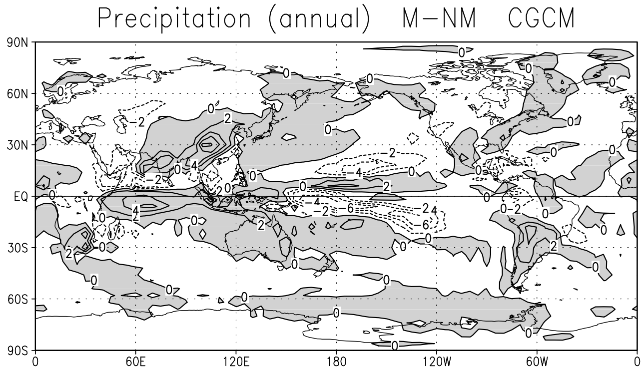


Fig. 2. Annually averaged difference (M-NM) in precipitation of CGCM. The contour interval is 2 mm d^{-1}.

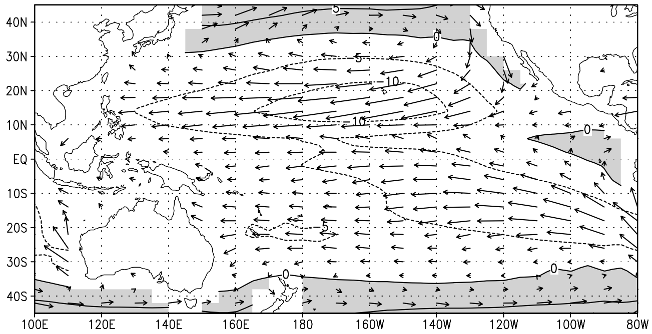
(M-NM) of the CGCM and SGCM, respectively. They are quantitatively similar except for some regions discussed below. Both in the CGCM and SGCM, most interior regions of Eurasia and North America are covered with positive temperature anomalies, while negative temperature anomalies are found over South Asia and East Asia on the southern and eastern peripheries of the Tibetan plateau.

Figure 2 shows the annual mean precipitation changes in the CGCM. A negative temperature anomaly over South Asia and East Asia is associated with a positive precipitation anomaly. Mountains create a heat source in the mid-troposphere and extend monsoon circulation and precipitation farther north onto the Asian continent (Hahn and Manabe, 1975). The Asian summer monsoon in M is stronger than that in NM. Increased precipitation moistens the ground, and wet ground favors local evaporation. Wet ground also decreases the sensible heat flux and lowers the surface temperature. Increased precipitation is associated with increased cloudiness, thus reducing solar insolation. This positive feedback loop maintains an increased precipitation and cooler surface temperature in M on the southern and eastern peripheries of the Tibetan plateau in summer.

In the continental interior, precipitation generally decreases with a mountain uplift. Similar to Broccoli and Manabe (1992), a larger westerly moisture flux and its convergence over northern Eurasia occurs in NM, while in M they are reduced. Drier conditions in M result in warmer adjusted surface temperatures than in NM because of less evaporative cooling.

SST decreases over large parts of the ocean with a mountain uplift. The simulated global mean SST difference is –0.8 K in the CGCM. A large SST decrease is found over the eastern Pacific Ocean, over the tropical Atlantic, and over the ocean near Japan (Fig. 1). Kitoh (1997) analyzed the SST changes in the SGCM and found that this SST decrease in M is explained by increased low-level clouds over the subtropical eastern oceans. These changes in the low-level clouds in the eastern Pacific Ocean is related to changes in the intensity of the subtropical

(a) Surface Wind Stress M CGCM



(b) Surface Wind Stress NM CGCM

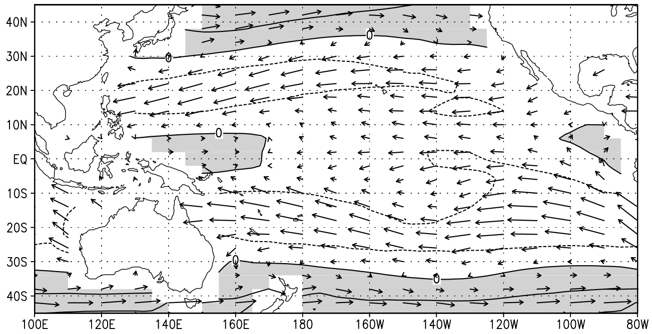


Fig. 3. Annually averaged surface wind stress in CGCM of (a) M and (b) NM. The contour interval is 0.05 N m^{-2}.

anticyclone. The strength of the summertime subtropical anticyclone in the North Pacific is related to the large-scale heat contrast between the continent and the ocean (Hoskins, 1996). Figure 3 compares the annual mean surface wind stress over the Pacific Ocean. Although the subtropical anticyclone still exists over the North Pacific in NM, it is much stronger in M in accordance with the stronger diabatic heating over the Eurasia continent throughout the troposphere. Stronger anticyclone and associated downdrafts are in favor of keeping moisture within the planetary boundary layer to make stratiform clouds over the subtropical eastern oceans, particularly in summer.

ROLE OF OCEAN GENERAL CIRCULATION

By comparing Figs. 1(a) and (b), we note a difference in the temperature changes to the east of Japan. At sea level, the Siberian high and the Aleutian low characterize the Eurasia–North Pacific in the present-day winter climate. Both are more intense in M than in NM. A cold surge from Siberia is stronger in M than in NM. The SST drop near Japan in Fig. 1(b) is related to changes in the cold air advection from the colder continent toward the warmer ocean in winter (Kutzbach *et al*., 1993). However, the SST decrease to the east of Japan in the CGCM is much smaller. This is explained by the larger heat transport by western boundary currents. As implied by a stronger subtropical anticyclone (Fig. 3), the oceanic subtropical gyre is stronger in M than in NM. The lower surface temperature in SGCM to the east of Japan is compensated by the larger heat transport, resulting in a smaller temperature response in the CGCM.

SUMMARY

Land surface temperature changes by orography can be summarized as a warmer continental interior and colder coastal area over land. The land surface temperature drops due to the lapse-rate effect. When this effect is eliminated, the continent interior becomes warmer with a mountain uplift because clouds become fewer and the surface drier due to a decreased moisture transport. On the other hand, South Asia becomes cooler because the summer monsoon is stronger, and heavier precipitation makes the land surface wetter and increases the clouds.

The SST is also modified by the existence of orography. Both the CGCM and SGCM show qualitatively similar results in a cooler SST in M particularly over the subtropical eastern oceans. This occurs because less solar radiation reaches the surface due to more low-level clouds that are induced by a strong subtropical anticyclone. The subtropical gyre is stronger in M than in NM, and therefore, Kuroshio is stronger in M. This difference in ocean circulation may explain the quantitatively different response to the east of Japan between the CGCM and SGCM.

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