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Mountain uplift and surface temperature changes

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Abstract. Mountain uplift significantly affects both sea surface temperature (SST) and land surface temperature. This was studied using a coupled atmosphere/mixed layer ocean model with and without mountains. The global mean SST dropped 1.4°C with mountain uplift, mainly due to increased lower tropospheric clouds in the subtropical eastern Pacific. Increased clouds hinder solar radiation into the ocean and lower SST. The increased frequency of stratus incidence is related to subtropical anticyclones intensified by a strong temperature contrast between the continent and ocean in mountainous regions. Land surface temperature drops due to the lapse-rate effect. When this effect is eliminated, the continental interior does not become as cool with mountain uplift because clouds become fewer and the surface drier due to decreased moisture transport. Southern Asia becomes cooler because monsoon-induced precipitation wets the ground and increases clouds. Our result showed greater northern high latitude temperature changes than the previous study, indicating the importance of cloud-related feedback in paleoclimate modeling.

Introduction

Large-scale mountains such as the Tibetan plateau and the Rockies play an important role in the earth's climate system through dynamical and thermodynamical effects (Kasahara et al. 1973; Manabe and Terpstra 1974; Hahn and Manabe 1975; Tokioka and Noda 1986). Geological evidence shows that the last 10-20 million years have seen a significant uplift in the Tibetan plateau (Ruddiman et al. 1989; Harrison et al. 1991). General circulation model (GCM) studies were made to clarify climatic change accompanying this uplift (Kutzbach et al. 1989; Ruddiman and Kutzbach 1989; Prell and Kutzbach 1992; Kutzbach et al. 1993).

Most earlier GCM studies of the effects of orography on the earth's climate were conducted using atmospheric GCMs that prescribed the SST as a boundary condition. These models thus severely limited model sensitivity by neglecting atmosphere-ocean interaction and sea ice changes. Kutzbach et al. (1993) used an atmosphere/mixed layer ocean-coupled model to investigate climatic changes due to mountain uplift. Atmosphere/mixed layer ocean-coupled models, which allow the SST to change with atmosphere-ocean heat flux exchange, are used extensively for equilibrium CO_2 doubling experiments and paleoclimate simulations. In this paper, we use an atmosphere/mixed layer ocean-coupled model to investigate climatic changes due to mountain uplift. Discussions focus on surface temperature changes both over land and ocean.

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Model and experiment

The atmosphere/mixed layer ocean-coupled model used for this study is based on the MRI global ocean-atmosphere coupled GCM (Tokioka et al. 1995). The atmospheric model has a horizontal resolution of 4° latitude by 5° longitude and 15 vertical levels with its top at 1 hPa. Both seasonal and diurnal solar insolation cycles are included. The oceanic model is replaced with a constant 50-m depth slab ocean model. A sea ice model, also included, calculates sea ice concentration and thickness. To compensate for the absence of heat transport by ocean currents and upwelling, a heat flux adjustment term is added to the equation that calculates the SST. The model was integrated for 12 model years with a realistic land-sea distribution and orography (M run) and with a flat surface everywhere by keeping the same land-sea distribution (NM run). Elevation of the highest point over Tibet is 4,400 m in M. Averages are taken from the last 5 years of integration when the global mean SST and sea ice are near equilibrium.

Land surface temperature changes

In the annual average surface temperature difference (M minus NM) (Fig. 1a), general cooling occurs in the surface temperature with mountain uplift. Global mean temperature change is -6.4°C over land and -1.4°C over ocean (Table 1). We begin with temperature change over land.

As temperature decreases with elevation, most temperature changes in mountainous regions are natural and affected by this "lapse-rate effect." If we adjust surface temperature changes assuming a typical environmental lapse rate of 6.5 K km^{-1}, most interior regions of Eurasia and North America would now be covered with positive temperature anomalies (Fig. 1b). Negative temperature anomalies are still found over South Asia and East Asia on the southern and eastern periphery of the Tibetan plateau.

These temperature changes are related to changes in precipitation, soil moisture, and cloudiness (Fig. 2). Mountains create a heat source in the middle troposphere and extend monsoon circulation and precipitation farther north onto the Asian continent (Hahn and Manabe 1975). The Asian summer monsoon in M is therefore substantially stronger than that in NM. Increased precipitation wets the ground (Fig. 2a-b), and wet ground favors local evaporation, which feeds back as precipitation. Wet ground effectively decreases sensible heat flux and lowers surface temperature. Increased precipitation is associated with increased cloudiness (Fig. 2c), reducing solar insolation reaching the ground to maintain lower surface temperatures. This positive feedback loop maintains increased precipitation and cooler surface temperature in M on the southern and eastern periphery of the Tibetan plateau.

The situation differs in the interior of the Eurasia continent, where precipitation, cloudiness, and soil moisture

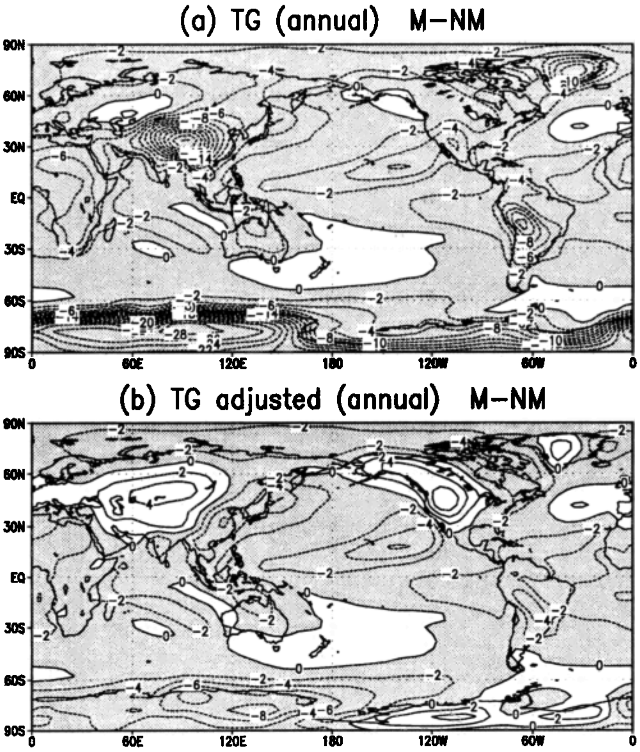

Figure 1. (a) Annually averaged surface temperature difference between mountain and no-mountain runs. The contour interval is 2 K. (b) Same as (a) except the temperature for the mountain run is adjusted by 6.5 K km^{-1}, the environmental lapse rate.

decrease with mountain uplift (Manabe and Broccoli 1990; Broccoli and Manabe 1992). In NM, a large westerly moisture flux exists from the Atlantic to the Eurasia continent. This is weakened significantly in M. Lower precipitation in M is maintained by lower moisture flux convergence and decreased local evaporation. Drier conditions in M result in warmer adjusted surface temperatures than in NM.

SST changes

In this experiment, we obtained large SST changes. The simulated global mean SST difference is -1.4°C with mountain uplift. A large SST decrease is found over the eastern Pacific Ocean, over the tropical Atlantic, and over the ocean off Japan (Fig. 1b). In this section we look into mechanism of this SST change.

It has been demonstrated by previous atmospheric GCM experiments that the most notable dynamic effect of mountains is on the stationary wave structure in northern hemisphere winter (Manabe and Terpstra 1974; Hahn and Manabe 1975; Tokioka and Noda 1986). 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. The existence of the Tibetan plateau in M helps accumulate cold air over Siberia. A strong anticyclone does not form in Siberia in winter without mountains, and a weaker one is situated over China (not shown). A similar pressure redistribution occurs over North America. Cold surge (outbursts of cold air from Siberia propagating southward along the eastern periphery of the Tibetan plateau) is also affected by the existence of the plateau itself (Nakamura and Murakami 1983), and is stronger in M than in NM. The SST drop off Japan is related to changes of cold air advection from the colder continent toward the warmer ocean in winter (Kutzbach et al. 1993).

Another, more important mechanism behind the SST change in this experiment is cloud feedback over the open sea (Table 2). The ocean surface heat budget consists of shortwave radiative flux (SR), longwave radiative flux (LR), latent heat flux (FW), and sensible heat flux (FS) and prescribed ocean heat transport. The SR decrease with mountain uplift is mainly balanced by decreased evaporative heat loss (FW) in an annual mean sense. This SR decrease is due to increased cloudiness (Table 1). Clouds have two compelling radiative effects: cooling by reflecting incoming solar radiation and warming by absorbing and reemitting longwave radiation. Observation shows the net cooling effect of present-day clouds (Ramanathan et al. 1989). Simulated global cloud-radiative forcing is -16.7 W^{-2} in NM and -20.6 W m^{-2} in M, so the cooling effect of clouds is intensified with mountain uplift.

To determine the mechanism behind cloud feedback, we studied seasonal characteristics. The dominant term in June-August (JJA) over the Northern Hemisphere ocean is SR, while that in December-February (DJF) is FW (Table 2). The increase in cloudiness with mountain uplift is great in

TABLE 1 **Annual mean area-averaged values.**

	G			L			O		
variable	M	NM	Δ	M	NM	Δ	M	NM	Δ
T (°C)	15.0	17.8	-2.9	8.7	15.0	-6.4	17.5	18.9	-1.4
T* (°C)	16.6	17.8	-1.3	14.3	15.0	-0.7	17.5	18.9	-1.4
P (mm d^{-1})	2.93	3.15	-0.22	2.97	2.98	(-0.01)	2.86	3.13	-0.27
C (%)	67.0	66.2	0.7	59.0	58.8	(0.2)	70.5	69.3	1.2

T: surface temperature (°C), T*: surface temperature (°C) adjusted for lapse-rate effect, P: precipitation (mm d^{-1}), and C: cloudiness (%) for cases M, NM, and M minus NM (Δ). Area averages are taken for global (G), land (L), and ocean (O). Differences in parentheses are not statistically significant at the 95% level.

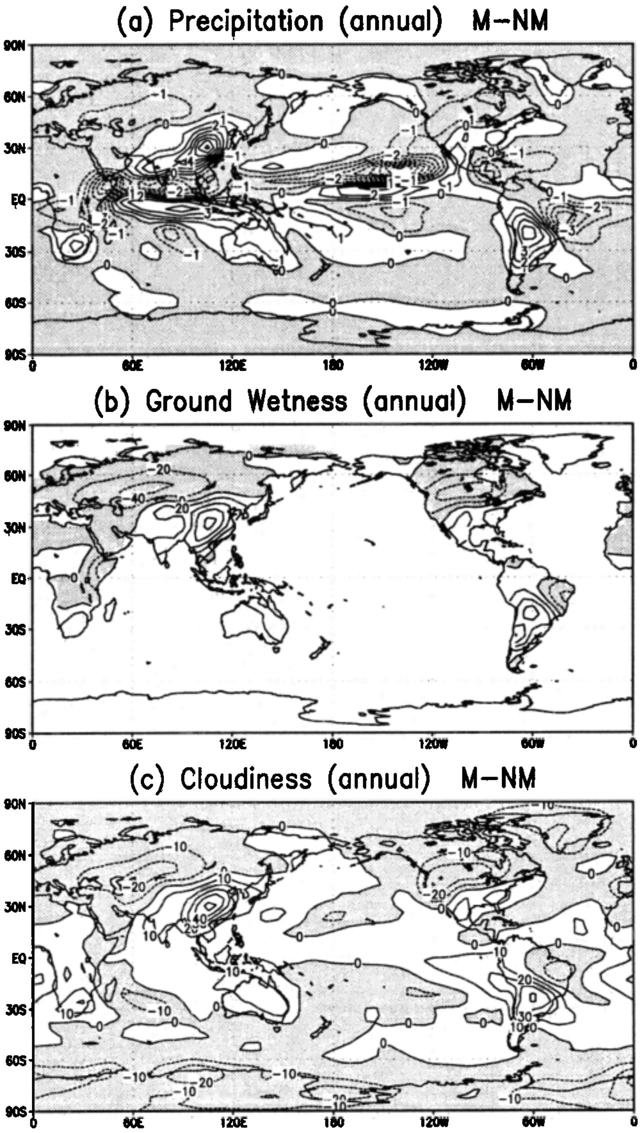

Figure 2. Annually averaged differences between mountain run and no-mountain runs for (a) precipitation, (b) soil moisture, and (c) cloudiness. Contour intervals are 1 mm d^{-1} for (a), 20% for (b), and 10% for (c).

summer, which contributes to the large decrease in SR. It was found in JJA that stratiform cloud increased with mountain uplift, particularly over the subtropical eastern Pacific between Hawaii and California, where stratocumulus is frequently observed in summer. The SST in eastern boundary current regions cooler than other longitudes favors persistent low clouds, while low clouds maintain a low SST by its radiative effect (Miller and Del Genio 1994). In the present GCM, the predicted temperature and moisture of the planetary boundary layer (PBL) are used to determine the thickness of a saturated layer near the PBL top (Randall 1976). Intense cloud-top radiative cooling and the cold SST allow the upper part of the PBL to remain saturated, and this moist and cool PBL contains extensive stratocumulus off California in summer.

These changes in stratiform clouds in the eastern Pacific Ocean may be related to changes in the intensity of the subtropical 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). The heating contrast of the high and middle latitudes, not the tropical, develops the subtropical anticyclone and makes it asymmetric east-west (Nikaidou 1990). Although the subtropical anticyclone is simulated 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.

Feedback of SST change on land surface temperature

Ocean surface temperature changes should have non-negligible effects on land surface temperature. To determine the effects of SST changes with mountain uplift, we also ran an atmospheric GCM with and without mountains for 10 years. In this experiment, the SST was prescribed as seasonally varying climatological values (Fig. 3). The global mean surface temperature differences (M minus NM) are -2.9°C for the coupled model and -1.3°C for the uncoupled atmospheric GCM with fixed SST. If we calculate area averages over land, the temperature change with mountain uplift holding SST fixed is -4.7°C, again smaller than the -6.4°C obtained in the coupled model (Table 1). Therefore this -1.7°C land surface

TABLE 2 **Heat budget components averaged over the ocean.**

	ANN-O			DJF-NHO			JJA-NHO		
variable	M	NM	Δ	M	NM	Δ	M	NM	Δ
SR ($W m^{-2}$)	157.3	163.5	-6.2	131.4	134.8	-3.4	200.3	214.9	-14.7
LR ($W m^{-2}$)	-41.2	-40.1	-1.2	-49.1	-46.7	-2.4	-37.5	-39.2	1.6
FW ($W m^{-2}$)	-96.0	-104.9	8.9	-125.5	-139.2	13.8	-89.5	-93.5	4.1
FS ($W m^{-2}$)	-17.4	-15.7	-1.8	-26.2	-24.4	-1.9	-8.2	-6.0	-2.2

SR: net solar insolation ($W m^{-2}$), LR: net longwave flux ($W m^{-2}$), FW: latent heat flux ($W m^{-2}$), and FS: sensible heat flux ($W m^{-2}$) for cases M, NM, and M minus NM (Δ). Positive means downward flux. Averages are taken for annual mean global ocean (ANN-O), December-February mean Northern Hemisphere ocean (DJF-NHO), and June-August mean Northern Hemisphere ocean (JJA-NHO). All differences (Δ) are statistically significant at the 95% level.

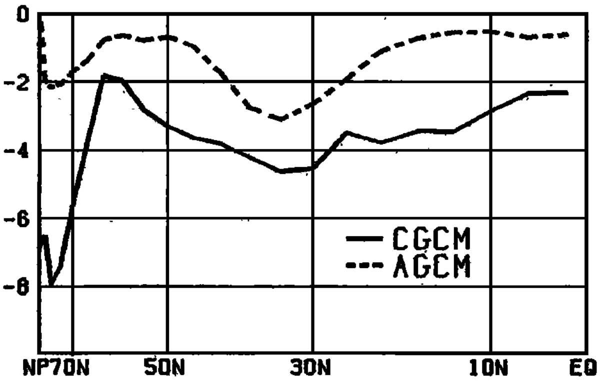

Figure 3. Latitudinal distribution of annually averaged zonal-mean surface temperature difference between mountain and no-mountain runs. The solid line is for the atmosphere/mixed layer ocean-coupled model and the dashed line for the atmospheric GCM.

temperature difference is associated with the SST change of -1.4°C. The larger response over the continent than over the ocean is mostly due to snow-albedo feedback and changes in cloudiness, particularly in summer, over the high-latitude continent (Saito and Tokioka 1994).

Conclusion

In the context of paleoclimate modeling, it is argued that uplift-related cooling in high latitudes is not sufficient to fully explain late Cenozoic vegetation change, and additional mechanisms such as higher CO_2 levels must be included to bring simulated climates into closer agreement with geologic evidence (Harrison et al. 1991). We have shown that land surface temperature is decreased more by mountain uplift in the model where the SST is allowed to change than in the model where the SST is fixed.

Kutzbach et al. (1993) used a coupled model, obtaining a global mean surface temperature change of -1.4°C with mountain uplift – about half the value obtained by our experiment. This discrepancy comes from the different sensitivities of ocean surface temperatures between the two models. Low clouds play the major role in regulating the SST in our model, so the discrepancy between the two models may come from different cloud parameterization and different model climates. Applying climate model simulations to paleoclimate issues by quantitatively comparing them to geological evidence should take into account model-to-model divergence.

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