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Thematic Article

Sensitivity of the central Asian climate to uplift of the Tibetan Plateau in the coupled climate model (MRI-CGCM1)

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Abstract The relationship between the altitude of the Tibetan Plateau and climate change in central Asia was investigated through a numeric experiment using the Meteorological Research Institute (MRI) coupled atmosphere–ocean general circulation model I (MRI-CGCM1). The results suggest that summer precipitation in central Asia decreased significantly as the Tibetan Plateau rose in height. Spring precipitation, however, increased during initial growth stages when the plateau height was up to 40% of its present-day height, and then decreased with further plateau growth. During the Tibetan Plateau uplift, the difference between precipitation and evaporation was minimal during spring. When the plateau attained a height exceeding 60% of its present height, relatively low precipitation but high evaporation in spring led to a lower amount of ground moisture. In the case of the high plateau, sensible heat flux during summer and fall largely exceeded latent heat flux. Change was particularly significant for cases when the plateau reached 40–60% of its present-day height. The duration of the predominant sensible heat flux became longer with the uplift of the Tibetan Plateau. The period in which latent heat exceeded sensible heat seems to have been restricted to winter and early spring. The numeric experiments suggest that a significant drying of central Asia corresponded to the period in which the Tibetan Plateau exceeded approximately half its present-day height.

Key words: arid climate, central Asia, general circulation model, Tibetan Plateau uplift.

INTRODUCTION

The Tibetan Plateau plays an important role in present-day climate formation not only in Asia, but also globally. The Tibetan Plateau creates dynamic and thermodynamic atmospheric effects (Kutzbach *et al*. 1993) and influences ocean circulation through atmosphere–ocean interactions. The Tibetan Plateau also helps induce and maintain Asian monsoon circulation, including the southwesterly winds that exist at lower levels of the troposphere and the anticyclonic circulation at the upper levels. The current Asian climate depends highly on atmospheric monsoon circulation, related land-surface conditions, including vegetation and soil moisture, and the surrounding ocean. In conjunction, land and ocean conditions relate to variations in the Asian monsoon on interseasonal, interannual and decadal scales.

The Tibetan Plateau began to rise during the early Tertiary as a result of collision between the Indian and the Eurasian Plates. This rise has altered the Asian climate (An *et al*. 2001). Some global climate change events from the early Tertiary to the present were also likely connected with the uplift of the Tibetan Plateau. To accurately understand the monsoon system, the global climate system and their interrelationship, it is thus necessary to investigate the role of the Tibetan Plateau in the climate system and the relationship

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between the Tibetan Plateau uplift and past climate change, including the evolution of the Asian monsoon. However, it is difficult to determine the influence of plateau uplift from geological evidence alone. Hence, to obtain numeric estimates for past climate change related to the uplift of the Tibetan Plateau, a quantitative evaluation is necessary.

General circulation models (GCM) were developed to examine the theoretical mechanisms of various atmospheric or oceanic phenomena on climatic change. Several GCM studies have investigated the effects of the Tibetan Plateau on the Asian monsoon. Most of the previous model studies compared a mountain run (M) and no-mountain run (NM) using either the atmospheric GCM (AGCM; Manabe & Terpstra 1974; Hahn & Manabe 1975; Broccoli & Manabe 1992) or the coupled atmosphere–ocean GCM (CGCM or AOGCM; Kitoh 1997, 2002). However, these studies were unable to reveal the relationship between orographic altitude and climate change. In fact, in the real climate system, orography plays a role in forming sea surface temperature (SST) distributions and oceanic circulations via atmospheric circulation. Few studies using coupled GCM have considered orographies while accounting for the effects of altitude on climate and the Asian monsoon system. The effects of changing oceanic general circulation should be considered to fully understand orographic effects on climate evolution. The relationship between the Asian summer monsoon and tropical Pacific conditions is significant for the formation of the tropical climate. It is therefore essential to investigate controls on the tropical summer climate over the Pacific and the Indian Oceans as a coupled atmosphere–ocean system that includes the Asian summer monsoon.

For these reasons, systematic numeric experiments using the Meteorological Research Institute (MRI) CGCM were conducted to investigate climate change due to the progressive uplift of large-scale orographies. However, because of the scarcity of comprehensive and global data on orographic altitudes for the geological past, altitudes of present-day global orographies were simply adjusted in our experiments. The resulting changes in the Asian summer monsoon and the coupled atmosphere–ocean system in the tropics in summer were investigated by Abe *et al.* (2003, 2004), who focused on the evolution of the Asian summer monsoon and change in the moist summer climate in southern Asia. However, as Broccoli and Manabe (1992) noted, aridity in central Asia, mostly northwest and north of the Tibetan Plateau, is related mainly to the existence of the Tibetan Plateau and the evolution of the Asian summer monsoon, which was influenced by formation of a trough in the mid-level troposphere and enhanced subsidence in central Asia. Furthermore, a study by Kitoh (2002) showed a decrease in precipitation and warming in central Asia as a result of mountain uplift. Thus, clarification of the relationship between the formation of an arid climate in central Asia and the altitude of the Tibetan Plateau is necessary to understand climate change associated with Tibetan Plateau uplift. The present paper describes climate change in central Asia associated with the progressive uplift of the Tibetan Plateau using data acquired in the same experiment as Abe *et al.* (2003, 2004).

MODEL AND EXPERIMENTAL DESIGN

The numeric experiment was conducted using the MRI CGCM I (Tokioka *et al.* 1995). The horizontal resolution of the atmospheric part was 5° longitude and 4° latitude, and the atmosphere exhibited 15 vertical layers, the topmost at 1 hPa. A seasonal and diurnal progression of shortwave radiation was introduced, and the absorption and scattering of shortwave radiation by ozone and water vapor were calculated in the model. The scheme of cumulus convection was the modified Arakawa–Schubert scheme (Tokioka *et al.* 1988), and cloud was diagnostically predicted. A calculation of longwave radiation was also included. The land surface model had four vertical layers, and the ground wetness, frozen soil moisture and ground temperature were calculated prognostically at each level of land. The land-surface processes did not explicitly include vegetation effects. The present-day orography used in the GCM is shown in Figure 1. Although accurate characteristics of the mountains were not resolved because of coarse spatial resolution, features of large-scale orographies such as the Tibetan Plateau and North American Rockies were easily recognizable. The details of atmospheric phenomena are described in Kitoh *et al.* (1995).

The oceanic section of the GCM was developed at the MRI (Nagai *et al.* 1992). The horizontal resolution of the ocean in the GCM was 2.5° longitude and 2.0° latitude, but the resolution between 12°S and 12°N latitude was finer for simulating realistic oceanic phenomena in the tropics. The ocean model had 21 vertical layers and a realistic topography of the ocean bottom.

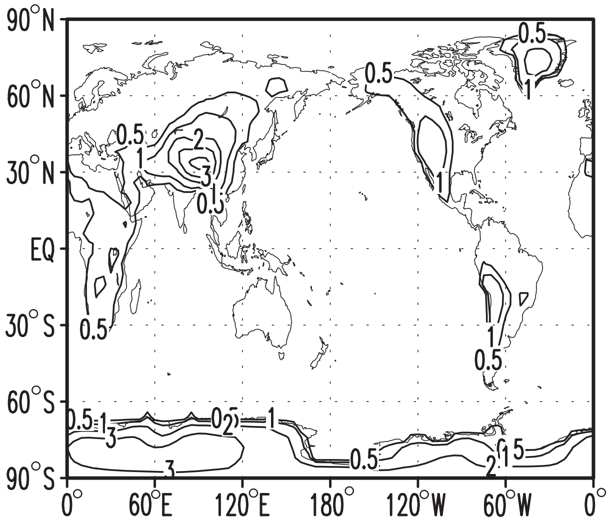

Fig. 1 The present-day topography used in the Meteorological Research Institute coupled general circulation model. Contour heights are in kilometers. EQ, equator.

A 6-h interval was used for the exchange of water and energy between the ocean and the atmosphere. The flux adjustment for surface energy and water was set to produce realistic SST and sea surface salinity fields. In this simulation, sea ice conditions were specified using a monthly climatology based on observations.

Six experimental runs were performed (M0, M2, M4, M6, M8 and M), each of which was integrated for 50 years, corresponding to varying heights (0, 20, 40, 60, 80 and 100% of the global topography at present). Land surface distribution was the same in all runs. All run calculations began with the same initial current climate condition. Abe *et al.* (2003, 2004) described the experimental design in detail. The present study used monthly mean data averaged for the past 30-year (21–50) integrations in each run.

CLIMATE CHANGE IN THE MID-LATITUDE REGION OF ASIA

Figure 2 illustrates longitude–time cross-sections of precipitation averaged for 35–45°N. In M0, precipitation between 40 and 70°E in central Asia was highest in June, when the amount was more than 4 mm/day, whereas the lowest values were found in September and October. However, the precipitation values in eastern central Asia were lower than 0.5 mm/day in October and November. In M0, lower precipitation in the mid-latitude region of Asia occurred during late summer and fall. When the height of the Tibetan Plateau was 20% of the present altitude, precipitation in east Asia increased markedly in summer, as noted in Abe *et al.* (2003), but precipitation levels between March and May both increased and migrated westward more than those in summer. Furthermore, an increase in fall precipitation was observed from M0 to M2. Thus, the lower precipitation during fall in the eastern region disappeared, while the drop in precipitation in the western region remained. In M4, precipitation of more than 3 mm/day in March and April was found in a wide area. Precipitation from late spring to summer in east Asia increased in association with the evolution of the Asian summer monsoon as a result of uplift of the Tibetan Plateau. However, a lower precipitation period existed in central Asia, and a pronounced decrease in precipitation

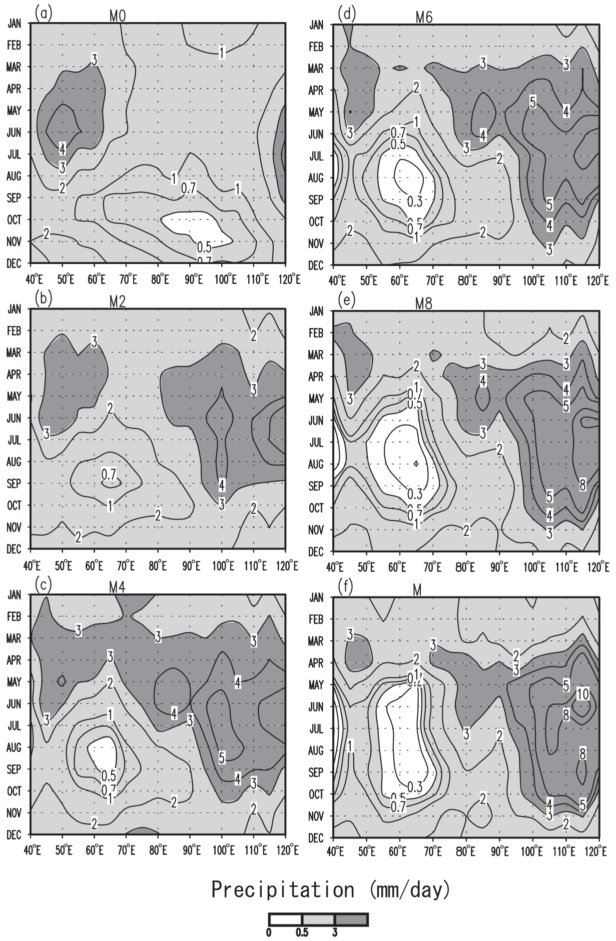

Fig. 2 Longitude–time (monthly) cross-sections of precipitation averaged for 35–45°N for all runs. (a) M0, (b) M2, (c) M4, (d) M6, (e) M8 and (f) M correspond to model runs in which the height of the Tibetan Plateau was 0, 20, 40, 60, 80 and 100% of the present height, respectively. Units are mm/day. Precipitation ranges of <0.5, 0.5–3.0 and >3.0 mm/day are shown in white, light gray and dark gray, respectively.

occurred during August and September Between 55 and 75°E, a contrasting change from M0 to M4 existed between spring and fall; an increase in spring was seen and a decrease in fall was shown. Thus, a relatively large amplitude in the seasonal progression of precipitation was shown for M4. When the Tibetan Plateau attained 60% of its present altitude, precipitation in central Asia decreased during all seasons, whereas it increased in east Asia. In central Asia, the smallest precipitation appeared in August, and a precipitation level of less than 2 mm/day continued from May to November. In summer, precipitation between 75 and 95°E decreased gradually with the season's progression. In M8, a decrease in precipitation occurred during late spring and summer in central Asia. The period when precipitation was lower than 0.5 mm/day extended from June to September.

The uplift of the Tibetan Plateau from M8 to M led to a further decrease in summer precipitation in central Asia. From M6 to M, precipitation in east Asia increased gradually in association with the evolution of Asian monsoon circulation; precipitation of more than 3 mm/day was then maintained from May to October, although the summer precipitation appeared to be over-simulated in the northern part of eastern China in the control run (M). However, the region between 75 and 90°E experienced a decrease in summer precipitation in all runs except M0. As the Tibetan Plateau rose from M0 to M, summer precipitation decreased in central Asia, a finding that is consistent with that of Broccoli and Manabe (1992). In M0, the lowest precipitation in central Asia occurred in September, whereas the summer precipitation decreased with the uplift of the Tibetan Plateau. In central Asia, precipitation during spring increased from M0 to M4; from M4 to M, however, spring precipitation decreased and the duration of this lower precipitation was extended. The tendency toward change in spring precipitation from M0 to M4 differed from that from M4 to M. The interesting relationship between the precipitation decrease and Tibetan Plateau uplift was found not only in summer but also during spring.

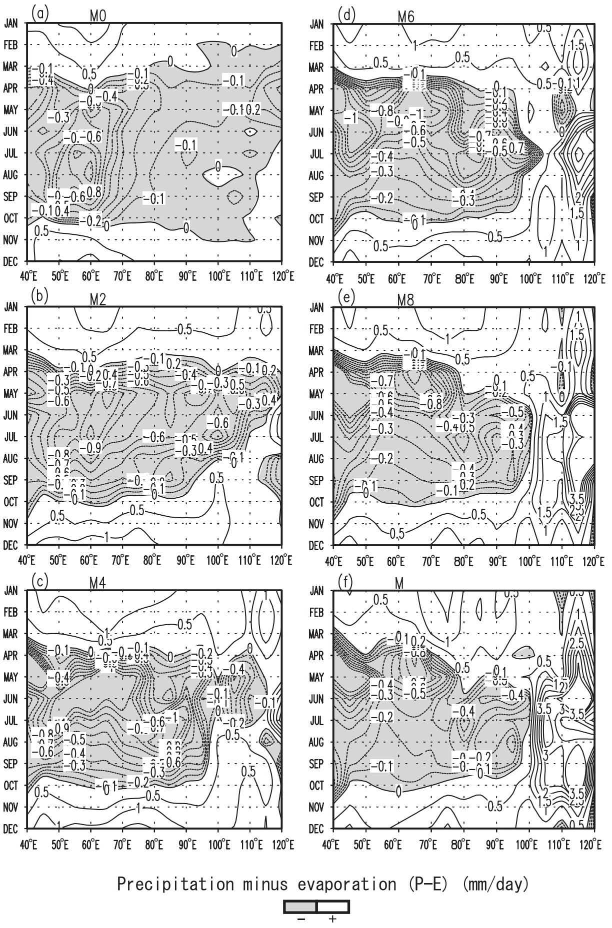

Fig. 3 Longitude–time (monthly) cross-sections of the difference between precipitation and evaporation averaged for 35–45°N in all runs. (a) M0, (b) M2, (c) M4, (d) M6, (e) M8 and (f) M correspond to model runs in which the height of the Tibetan Plateau was 0, 20, 40, 60, 80 and 100% of the present height, respectively. Units of precipitation minus evaporation (P – E) are mm/day. Negative values are shaded.

An arid climate is generally defined as a state in which precipitation is less than evaporation. Figure 3 shows the longitude–time cross-sections of the difference between precipitation and evaporation (P–E) averaged for 35–45°N in all runs. In M0, there were negative values in a wide region between March and October, whereas central Asia had relatively small values. Decreases in P–E occurred to the east of 80°E for models M0 and M2, except where negative values during fall in east Asia changed to positive values. To the east of 100°E, negative values in M4 were restricted to April–July; the negative values then disappeared from M4 to M because of increasing precipitation. In contrast, the negative values of P–E to the west of 100°E were maintained between April and September. Although the smallest values in M0 in central Asia were found in August, those in the higher Tibet cases appeared earlier during the plateau's uplift. Ground wetness in central Asia gradually decreased with the uplift of the Tibetan Plateau in all seasons (not shown). In M2, ground wetness in central Asia was the lowest in August, and the duration of lower ground wetness became longer from M2 to M6. After M6, the duration of lower ground wetness had little effect in central Asia. In May, the ground wetness in M6, M8 and M fell to less than 20% of field capacity. Therefore, the evaporation in spring contributed directly to the decrease in ground wetness during the later stages of the Tibetan Plateau uplift. In the case of the high, uplifted plateau, low precipitation in central Asia was also attributed to a reduction in the surrounding moisture supply, because of the surrounding mountains and the predominant subsidence in central Asia accompanying the enhanced summer convection in the southeastern Tibetan Plateau region (Rodwell & Hoskins 1996). The low ground moisture conditions may have contributed to the enhancement of aridity in central Asia during summer and fall.

To evaluate changes in monthly mean precipitation with the uplift of the Tibetan Plateau more accurately, longitude–Tibetan altitude cross-sections of precipitation averaged for 35–45°N in April, June, August and October are shown in Figure 4. Cross-sections of differences in precipitation between successive stages are also shown in Figure 5. In April, an increase in precipitation clearly showed from M0 to M6 to the east of 70°E. However, in central Asia, precipitation of less than 3 mm/day appeared in M6, whereas it was slightly lower before M4. Figure 5a shows the biggest decrease in precipitation from M4 to M6 in April. There was an increase in precipitation from M0 to M in June in the area east of 100°E; in particular, a clear westward migration of greater precipitation was apparent in M4 (Fig. 5b). In central Asia, however, precipitation decreased gradually to less than 1 mm/day in M6. The decrease from M4 to M6 in June was relatively large compared with that in other successive stages. In addition, the decrease from M4 to M6 was widely observed in the area west of 100°E. Figure 4b shows precipitation of less than 1 mm/day in central Asia in M2. In August, while a decrease in precipitation occurred in central Asia with the uplift of the Tibetan Plateau, the rate of decrease from M6 to M8 was smaller than that in the lower Tibet cases. From M8 to M, an increase in precipitation was also found in central Asia. However, a decrease in precipitation from M4 to M6 was evident in August, similar to that seen during June. Thus, during summer the decrease in precipitation in central Asia from M6 to M was much more significant in June than in August. The precipitation decrease in central Asia during October was relatively small compared with that in other months. As shown in Figure 5d, however, relatively large decreases in precipitation were observed from M4 to M6. After M6, lower precipitation rates (less than 0.5 mm/day) appeared in central Asia.

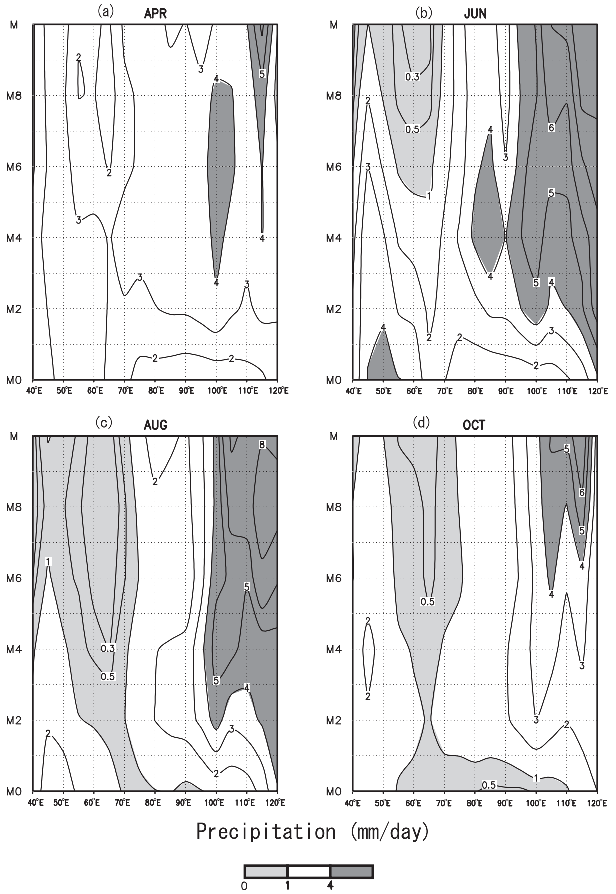

Fig. 4 Longitude–Tibetan altitude cross-sections of precipitation averaged for 35–45°N in (a) April, (b) June, (c) August and (d) October. Units are mm day^{-1}. M0, M2, M4, M6, M8 and M correspond to model runs in which the height of the Tibetan Plateau was 0, 20, 40, 60, 80 and 100% of the present height, respectively. The dark shaded area indicates precipitation of more than 4 mm/day, and lighter areas show precipitation of less than 1 mm/day.

To illustrate changes in surface air temperature in central Asia with the uplift of the Tibetan Plateau, longitude–time cross-sections of surface temperature, averaged between 35 and 45°N in all runs, are shown in Figure 6. In central Asia, the warmest temperatures occurred during summer, whereas temperatures east of 70°E decreased with the Tibetan Plateau uplift. In M0, summer temperatures in the area east of 70°E were higher than those to the west of 70°E. From M2 to M, summer temperatures east of 70°E fell to less than 30°C in M because of an increase in precipitation and uplift of the ground surface. In contrast, temperatures in central Asia increased gradually to more than 30°C in M. Therefore, a greater temperature gradient from west to east formed in the mid-latitude region of Asia as the Tibetan plateau was uplifted.

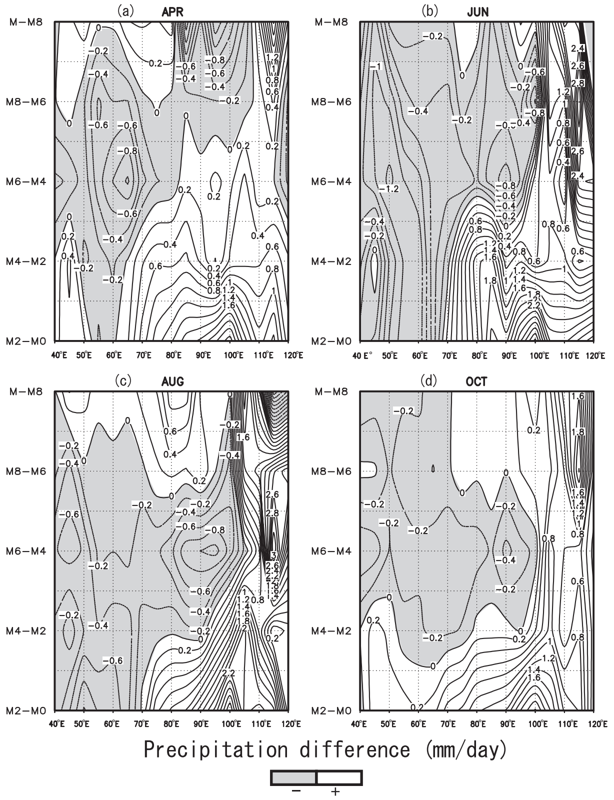

Fig. 5 Difference in precipitation averaged for 35–45°N for successive uplift stages plotted against longitude in (a) April, (b) June, (c) August and (d) October. Units of precipitation are mm/day. M0, M2, M4, M6, M8 and M correspond to model runs in which the height of the Tibetan Plateau was 0, 20, 40, 60, 80 and 100% of the present height, respectively. The shaded area shows negative values.

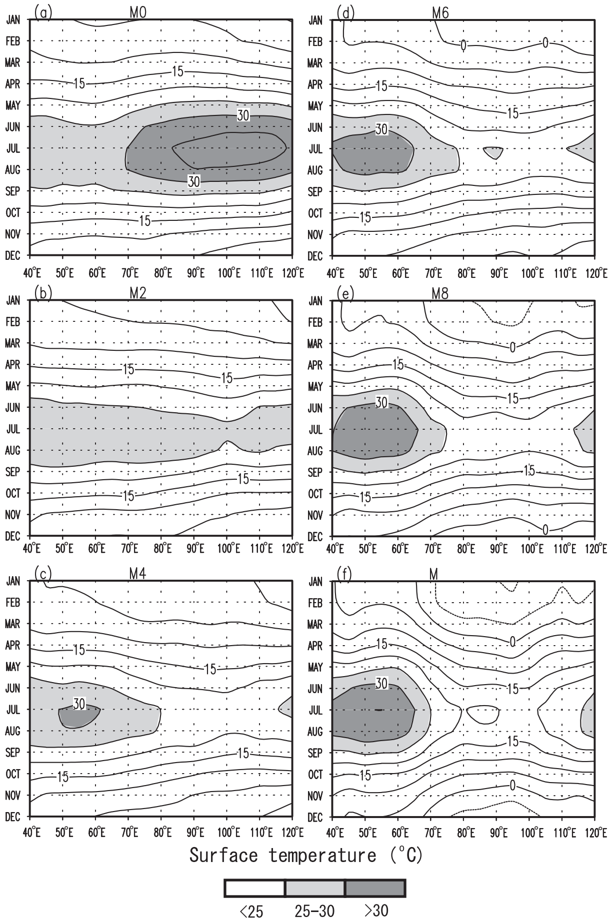

Fig. 6 The longitude–time (monthly) cross-sections of surface air temperature averaged for 35–45°N for all runs. (a) M0, (b) M2, (c) M4, (d) M6, (e) M8 and (f) M correspond to model runs in which the height of the Tibetan Plateau was 0, 20, 40, 60, 80 and 100% of the present height, respectively. Temperature is given in °C. Temperature ranges of <25, 25–30 and >30°C are shown in white, light gray and dark gray, respectively.

Furthermore, a decrease in temperature to the east of 70°E became evident during winter from M0 to M. This would have strongly affected the formation of the Siberian high in winter.

To describe spatial changes in surface temperature during summer associated with the uplift of the Tibetan Plateau, summer mean surface air temperatures, averaged for June–August in all runs, are presented in Figure 7. In M0, temperatures of more than 35°C were widespread in northern India and China, largely as a result of less precipitation and lower ground temperatures. Temperatures in Beijing, for instance, exceeded 30°C. When the Tibetan Plateau attained an altitude of 20% of its present height, cooling occurred in east Asia in relation to the remarkable increase in precipitation in the region and the increase in ground wetness, as noted by Abe *et al.* (2003). The region of temperatures more than 35°C disappeared entirely in M2. In M4, cooling in east Asia emerged because of an increase in precipitation and elevation of the ground surface. In particular, temperatures for the eastern Tibetan Plateau fell to less than 25°C. These temperatures contrasted with those in the west Asia region, including northern India and Iran–Afghanistan, which were characterized by temperatures of more than 35°C in M0. Little change in temperature occurred from M0 to M4 in this region. Furthermore, in M0, central Asia was cooler than eastern China. As the Tibetan Plateau attained heights of 20 and 40% of its present altitude, temperatures changed slightly in central Asia, as the temperature gradient from east to west along 40°N varied from positive to negative. As the Tibetan Plateau rose from M0 to M4, precipitation in eastern China increased markedly (Abe *et al.* 2003), which caused temperatures to decrease. However, although a slight precipitation decrease occurred in the Iran–Afghanistan region, it had little influence on temperature. Therefore, during the first stage of the Tibetan Plateau uplift, there appears to have been

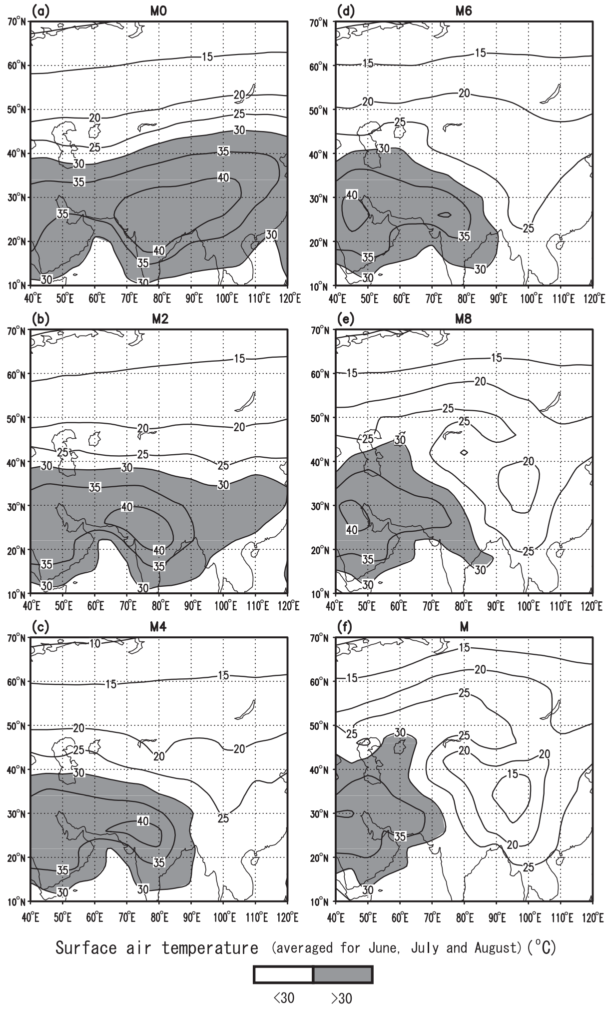

Fig. 7 Surface air temperature averaged between June and August for all runs. (a) M0, (b) M2, (c) M4, (d) M6, (e) M8 and (f) M correspond to model runs in which the height of the Tibetan Plateau was 0, 20, 40, 60, 80 and 100% of the present height, respectively. Temperature is given in °C. Temperatures of >30°C are shown in gray.

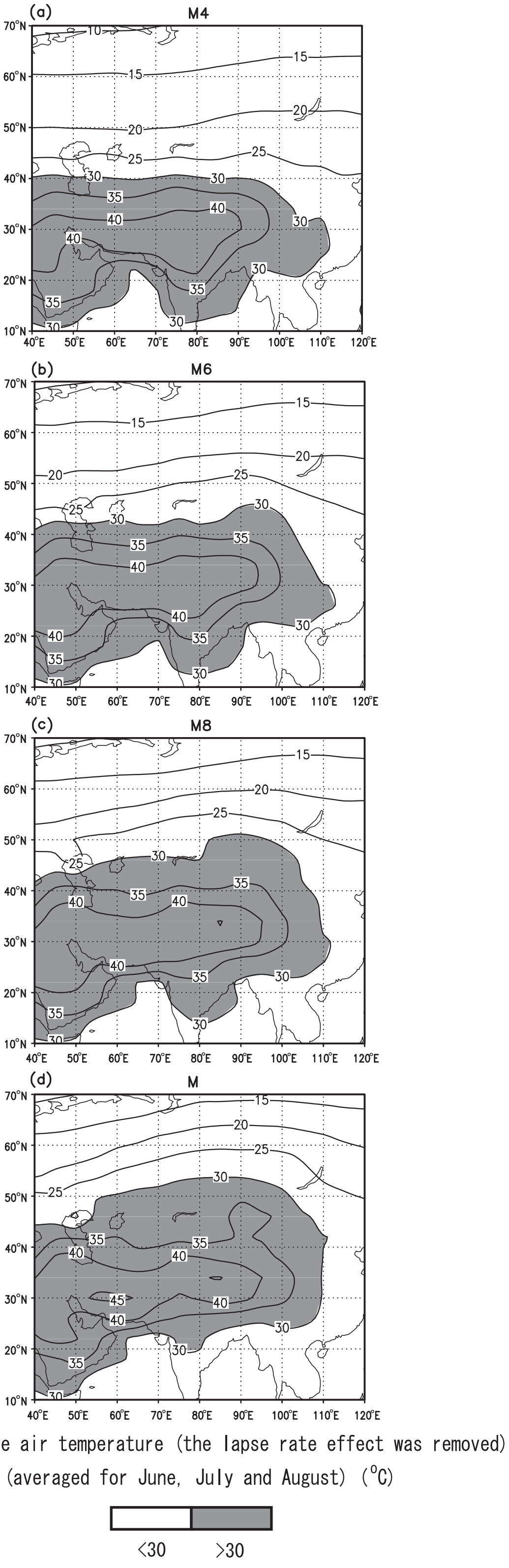

Fig. 8 Surface air temperature from which the lapse rate effect as a result of orography was subtracted, averaged between June and August, for four runs. (a) M4, (b) M6, (c) M8 and (d) M correspond to model runs in which the height of the Tibetan Plateau was 40, 60, 80 and 100% of the present height, respectively. The lapse rate effect was calculated with the standard lapse rate, 6.5 K/km, of atmosphere. Temperature is given in °C. Temperatures of >30°C are shown in gray.

a contrast in temperature between east Asia and west Asia, although the temperature in central Asia changed very little because of a slight decrease in precipitation. In M6, it seems that the area experiencing temperatures of more than 30°C migrated north in central Asia. Furthermore, from M6 to M, this warmer area was more wide spread in central Asia. The gradient in temperature also became positive from west to east along 50°N, and the obvious contrast in temperature fields in the middle latitudes of Asia appeared during the latest stages of the Tibetan Plateau uplift. Figure 8 shows the surface air temperature from which the lapse rate effect as a result of orography was subtracted in M4, M6, M8 and M, using the standard lapse rate of 6.5 K/km. From M0 to M4, little warming in summer was seen in central Asia, although cooling in east Asia occurred. However, a relatively marked warming in central Asia appeared in the high Tibetan Plateau cases (M6–M), as temperatures of more than 30°C northwest and north of the Tibetan Plateau migrated northward (Fig. 8). This warming related to low precipitation rates and low ground wetness. In contrast, there was evident cooling in east Asia, apparently related to an increase in precipitation rates and ground wetness. Thus, on the change in surface air temperature without the lapse rate effect, zonal temperature gradients between central and east Asia appeared.

CHANGE IN SEASONAL ENERGY BALANCES AT THE GROUND SURFACE

To examine changes in the surface energy balance and its seasonal progression associated with climate change in central Asia, including precipitation rates and surface temperature, various time series of area mean fluxes of latent heat, sensible heat and net radiation in central Asia in all runs are shown in Figure 9. Latent heat flux and sensible heat flux from the ground surface to the atmosphere were positive, while net radiation flux from the atmosphere to the ground surface was positive. Latent heat in M0 exceeded sensible heat between November and August, with a maximum in June. In September, however, sensible heat exceeded latent heat flux in central Asia, but the difference between latent heat flux and sensible heat flux was small. Latent heat flux in June decreased markedly with the uplift of the Tibetan Plateau. The maximum latent heat flux values in M2 and M4 were observed in May, whereas those of M6, M8 and M occurred in April. While latent heat flux decreased largely during May and June, with the Tibetan Plateau uplift, sensible heat flux increased. Thus, the sensible heat flux during June in M6 exceeded the latent heat flux. Furthermore, the sensible heat flux during May in M8 and M was larger than the latent heat flux. With the uplift of the Tibetan Plateau, the sensible heat flux in summer also increased, particularly in June. The sensible heat flux in M was maximized in June. Thus, the duration of greater sensible heat flux, rather than latent heat flux, was extended as the Tibetan Plateau rose. These results indicate that much of the ground surface energy during summer and fall in central Asia was applied toward an increase in air temperature. These results also show the relationship between a decrease in precipitation and uplift of the Tibetan Plateau. When the Tibetan Plateau was high, precipitation in spring decreased and moisture evaporated from the ground surface, as described in the previous section. As evaporation increased, ground surface moisture and the latent heat flux during summer in the higher Tibetan Plateau cases decreased, in contrast to the lower Tibetan Plateau cases. In fact, the sensible heat flux after spring increased to levels that exceeded the latent heat flux.

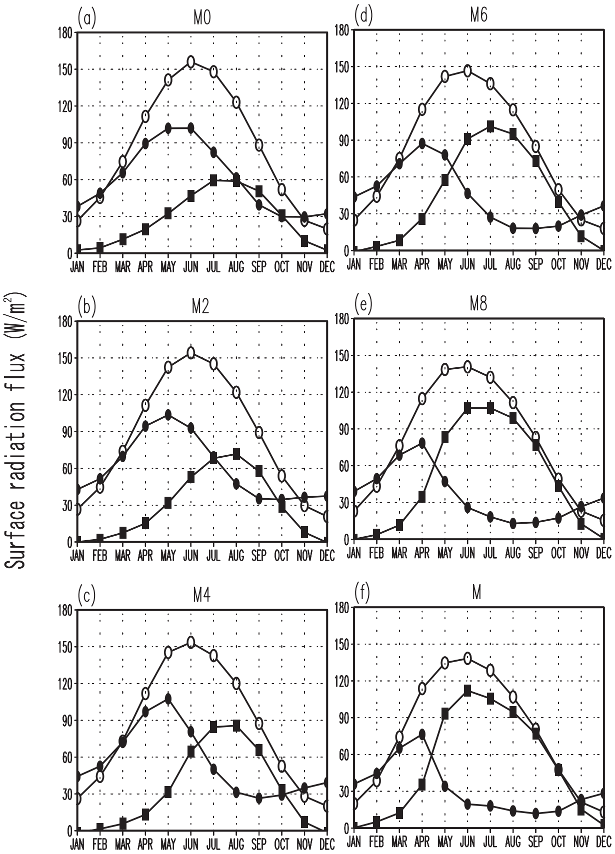

Fig. 9 Time series of the latent heat, sensible heat and net radiation fluxes averaged by area (55–70°E, 35–45°N) for all runs. (a) M0, (b) M2, (c) M4, (d) M6, (e) M8 and (f) M correspond to model runs in which the height of the Tibetan Plateau was 0, 20, 40, 60, 80 and 100% of the present height, respectively. Flux values are given in W/m^2. (○), Net radiation; (●), latent heat flux; (■), sensible heat flux.

From M4 to M6, the sensible heat flux increased markedly from April to September. In June, the sensible heat flux changed by approximately 30 W/m^2, and the sensible heat flux exceeded the latent heat flux. This result agrees with the decrease in precipitation and the northward expansion of warmth in summer. Therefore, this numeric experiment supports the hypothesis that drying in central Asia occurred conspicuously from M4 to M6, in comparison with changes seen in other successive uplift stages. Although a change in latent and sensible heat flux in spring seems to have taken place after M6 (Fig. 9), it was not as distinct a change as those corresponding with the lower Tibetan Plateau cases.

CONCLUSIONS

Prior to the formation of the Tibetan Plateau, a climate with lower precipitation rates existed in east Asia. At the same time, the climate in central Asia was wetter than that of east Asia, particularly during spring. As the Tibetan Plateau rose to 20% of its present height, summer precipitation in east Asia increased significantly (Abe *et al.* 2003). In central Asia, a low precipitation regime persisted during late summer and early fall. Precipitation rates in late summer and early fall decreased with increases in ground surface height (20–40%); the higher the Tibetan Plateau rose, the longer the duration of the low precipitation regime. In summer, precipitation in central Asia decreased markedly as the Tibetan Plateau rose. Precipitation increased in central Asia during the lower uplift stages (when the height of the plateau was 40% of its present altitude), but decreased with further height increases. Thus, the trend in precipitation change in spring in the lower stages of the Tibetan Plateau uplift differed from trends in the higher stages.

In the absence of an elevated Tibetan Plateau, the difference in precipitation and evaporation in central Asia was negative from April to September and reached a minimum in August. With the uplift of the Tibetan Plateau, the P–E difference was least in spring. During winter the ground in central Asia was relatively wetter. In spring the ground moisture decreased because of lower precipitation and a high degree of evaporation. This lower precipitation was attributed to a reduction in the moisture supply caused by the surrounding mountains and the predominant atmospheric subsidence during summer in central Asia, accompanied by enhanced summer convective activity over the southeastern Tibetan Plateau (Rodwell & Hoskins 1996). Such a low ground moisture situation could have contributed to enhanced aridity in central Asia during summer and fall, as noted by Broccoli and Manabe (1992). In addition, because of the low ground moisture situation, evaporation decreased, and thus the local flow of moisture from ground surface to air decreased. The low supply of moisture from the ground, in turn, contributed to low precipitation. A dominant increase in surface temperature then occurred. Although the change in precipitation was less than that in south and southeast Asia, the vegetation systems that depended on a local seasonal cycle of climate elements would likely have changed as a result of precipitation and temperature alterations associated with the Tibetan Plateau uplift. Plants that prefer a dry climate would have begun to appear in central Asia when the Tibetan Plateau reached higher altitudes.

The northward migration of a warm region seems to have occurred during summer with the uplift of the Tibetan Plateau. For cases when the Tibetan Plateau height reached 60% of its present height, temperatures of more than 25°C were found in central Asia. The warm region in the mid-latitude region of Asia expanded greatly with increased uplift (>60%). As a result, a distinct west–east temperature gradient formed between central and east Asia.

In cases when the height of the Tibetan Plateau was 40 and 60% of its present height, a comparatively pronounced decrease in precipitation was observed during spring, summer and fall in central Asia, with a remarkable increase in the surface air temperature. Variations in the latent and sensible heat fluxes in central Asia were also marked. The latent heat flux exceeded the sensible heat flux during spring and summer in the lower Tibetan Plateau cases. With the uplift of the Tibetan Plateau, however, the sensible heat flux increased gradually during summer and fall, while the latent heat flux decreased. In the higher Tibetan Plateau cases, the sensible heat flux distinctly exceeded the latent heat in summer and fall. The duration of dominant sensible heat flux increased with the elevation of the Tibetan Plateau, whereas the period in which the latent heat exceeded sensible heat was restricted to winter and early spring. Much of the energy obtained from the ground surface contributes to an increase in air temperature. Therefore, the air temperature in central Asia contrasted with that in east Asia and regions to the north, although the effect of ground-surface rise was noticeable. Furthermore, a distinct land–ocean temperature contrast appeared in the mid-latitudes; this contrast could have enhanced monsoon circulation over Asia and the North Pacific Ocean.

Although the present experiment cannot explicitly determine the timing of the uplift of the plateau, these results, combined with the geological evidence (Wang *et al.* 1999), suggests that the height of the plateau reached approximately half of the present mean altitude at the end of the Miocene. The study by Wang *et al.* (1999) showed evidence from pollen analysis that arid conditions have been restricted to northwest China since the latest Miocene, and then the driest climate occurred in the Pliocene and Pleistocene, which suggested that the plateau had reached approximately 1500 m height at the end of the Miocene. The present results show a drier climate appeared in central Asia, northwest of China, as the altitude of the Tibetan Plateau was higher than half of the present mean altitude. These results corresponds with those of Prell and Kutzbach (1992), suggesting that the altitude of the plateau reached up to half of the present altitude in the late Miocene from a comparison between results of a sensitivity experiment with a climate model and geological evidence. In contrast, Harrison *et al.* (1992) concluded from studies on tectonics that the mean height of the plateau had reached the present level by approximately 8 Ma. Guo *et al.* (2002) concluded from records of the loess deposits in China that by 22 Ma the southern margin of the plateau had reached an altitude high enough to cause desertification of the interior of the Asian continent throughout the year. If the mean plateau height had reached the present level in the late Miocene, the wet monsoon climate in south and east Asia would already have formed by the late Miocene, as suggested by climate model studies (Abe *et al.* 2003). However, An *et al.* (2001) indicated from paleo-climate proxies that the south and east Asian monsoon started at approximately 9–8 Ma, the latest phase of the Miocene. If this is the case, it may be difficult to conjecture that the Tibetan Plateau already existed as its present scale and height at the end of the Miocene.

With the uplift of the Tibetan Plateau, the climate in central Asia became dryer. The reasons behind this include a decrease in precipitation as a result of a reduction in the moisture supply from surrounding areas, the local moisture supply and predominant subsidence, which suppressed precipitation. Other contributing factors include decreased ground moisture because of less precipitation (Broccoli & Manabe 1992). The results of the present study imply that a dominant climate change of increased aridity in central Asia associated with the uplift of the Tibetan Plateau occurred after the Tibetan Plateau achieved at least half of its present height.

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