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Tibetan Plateau warming and precipitation changes in East Asia

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[1] Observational evidence presented here indicates that the surface temperatures on the Tibetan Plateau (TP) have increased by about 1.8°C over the past 50 years. The precipitation pattern that is projected as a result of this warming resembles the leading pattern of precipitation variations in East Asia (EA). Numerical experiments with atmospheric general circulation models show that atmospheric heating induced by the rising TP temperatures can enhance East Asian subtropical frontal rainfall. The mechanism of the linkage is found to be through two distinct Rossby wave trains and the isentropic uplift to the east of the TP, which deform the western Pacific Subtropical High and enhance moisture convergence toward the EA subtropical front. The model calculations suggest that the past changes in TP temperatures and EA summer rainfall may be linked, and that projected future increases in TP temperatures may lead to further enhanced summer frontal rainfall in EA region. **Citation:** Wang, B., Q. Bao, B. Hoskins, G. Wu, and Y. Liu (2008), Tibetan Plateau warming and precipitation changes in East Asia, *Geophys. Res. Lett.*, *35*, L14702, doi:10.1029/2008GL034330.

1. Introduction

[2] The EA monsoon rainfall affects the life of about one quarter of the world's population. The recent Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) reported that under the SRES A1B (a "middle of the road" estimate of future emissions) scenario, a 4°C warming will likely occur over the TP during the next 100 years [*Meehl et al.*, 2007]. This projected warming represents the largest elevated warming in the middle troposphere around the globe. The TP warming will not only melt glaciers that feed the rivers but also potentially change downstream precipitation. Current models do not give a robust consensus regarding the precipitation change in EA. Given such a large projected TP warming over a vast area of 2.5 million square kilometers with altitudes higher than 3,000 meters above sea level, the ways in which this may act to change EA rainfall during the coming years is of great scientific interest.

[3] On a geological time scale, the uplift of the TP has been known to have a profound influence on the formation of the Asian monsoon [*An et al.*, 2001; *Abe et al.*, 2003: *Kitoh*, 2004; *Kutzbach et al.*, 1993]. Variations in TP heating have also a profound effect on the seasonal cycle and interannual variations in the modern record [*Hsu and Liu*, 2003; *Liu et al.*, 2007; *Yanai and Wu*, 2006; *Ye and Gao*, 1979]. Observational studies have exhibited that TP heating can intensify EA monsoon by inducing the air pumping over TP and producing cyclonic spiral zonal-deviation circulation in the lower troposphere. [*Duan and Wu*, 2005; *Wu et al.*, 2007]. However, the physical processes by which a persisting warming over Tibet affects the downstream EA rainfall remain elusive.

2. Observed Trends in East Asian Summer Rainfall and TP Surface Temperature

[4] Figure 1a shows that over the past 48 years (1960–2007) the leading rainfall variability pattern over EA features enhanced rainfall along a southwest-northeast-oriented rain belt extending from the mid-lower reach of the Yangtze River Valley across South Korea to eastern Japan, which is primarily along the EA subtropical front (called *Meiyu* in Chinese, *Changma* in Korean, and *Baiu* in Japanese). The EA subtropical frontal rainfall has had an evident upward trend since 1960, with significant decadal variations superposed upon it (Figure 1b). Examination of the precipitation record for Seoul, Korea, which is one of the world's longest instrumental measurements of daily precipitation [*Wang and Ding*, 2006] indicates that the summer rainfall trend calculated for the pre-1950 period (1778–1949) is insignificant but the pronounced recent increasing trend since 1950 is unprecedented, which lends support to the trend shown in Figure 1a.

[5] The surface air temperature averaged over 90 Tibetan weather stations with elevations over 2,500 meters shows also a rising trend in the last 48 years (Figure 1b). While a majority of the stations are located in the eastern TP, Figure 1d indicates a coherent warming trend pattern over the whole TP. The upward trend in annual mean surface temperature averaged over the 90 stations is 0.36°C/decade during the period from 1961–2007 (Figure 1b), which doubles the previous estimation based on the data from 1955 to 1996 [*Liu and Chen*, 2000]. The rising temperature is supported by abundant evidence of recent glacial retreats in the same regions [e.g., *Shen*, 2004]. Note also that the surface warming trend persists throughout the annual cycle. Figure 1c shows that the precipitation pattern that is projected as a result of the TP surface air warming resembles the leading pattern of precipitation variations (Figure 1a), suggesting that the change in the TP thermal condition may link to the trend in the EA rainfall. However, the correlations do not warrant any cause and effect. Experiments with climate models are needed. In these models the temperatures over the TP can be varied and

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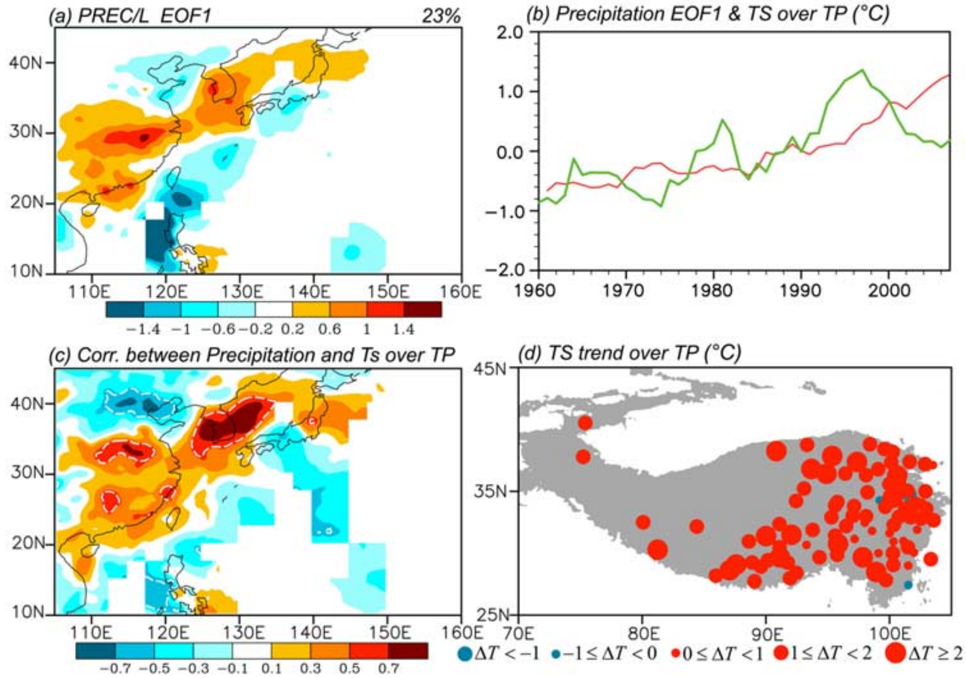

Figure 1. (a) Spatial pattern and (b) principal component (the green curve) of the leading mode derived from Empirical Orthogonal Function analysis of the five-year running mean June-August (JJA) rainfall over East Asia. The leading mode explains 23% of the total variance. The data used are obtained from precipitation data reconstructed over land (PREC/L) for the period 1960–2007 [*Chen et al.*, 2002]. The red curve (in units of °C) in Figure 1b shows the 5-year running mean TP surface air temperature averaged over 90 Tibet weather stations. (c) The correlation coefficient map of the JJA precipitation derived from PREC/L data with reference to the mean TP surface air temperature. Both the surface air temperature and PREC/L datasets were pre-processed by a 5-year running mean. The white dashed line stands for the regions where the correlation coefficients are statistically significant at 95% confidence level. (d) The linear trends in surface air temperature for the period 1961–2007 observed over 90 Tibet weather stations. The solid circles indicate the station locations and the shaded regions denote the areas with elevations over 2,500m. The size of the circles represents the magnitude of the warming.

the effects of the warming on the atmospheric flows and on rainfall can be studied.

3. Results From Numerical Experiments

[6] We performed numerical experiments with a comprehensive AGCM to see what effects raising the temperature over the TP will have on rainfall patterns to the east. The AGCM used is the ECHAM4 [*Roeckner et al.*, 1996]. To isolate the impacts of TP warming, in a control experiment and two sensitivity runs, we have forced the model with the same observed climatological SST and sea ice distribution and with fixed amounts of greenhouse gases and prescribed aerosols. The control run was integrated for 12 years and the last 10 years' integration was used to derive a reference state. The two sensitivity tests were integrated for 10 years each. The 10-year integrations were used to construct a 10-member ensemble (arithmetic) mean to reduce the uncertainties arising from differing initial conditions. The only difference between the control and sensitivity experiments is a change in land surface albedo over the TP region (27.5°N–37.5°N, 75°E–104°E). A reduction of albedo by 50% results in a TP surface warming (hereafter the "W" run), while an increase of albedo to 150% leads to a surface cooling (the "C" run). Since the W and C runs have similar spatial patterns but with opposite polarities, we examine the difference in ensemble means between the W and C runs, which is viewed as a departure from the long-term mean state induced by the TP warming.

[7] The artificial reduction of albedo over the TP results in a local surface air temperature increase by more than 2°C (Figure 2a), which mimics a TP warming scenario. In this case, precipitation increases significantly over the plateau, especially over its southern flank (Figure 2a). Note that the rainfall anomaly pattern shown in Figure 2a bears an overall similarity to the observed trend pattern (Figure 1a) and the pattern that is coherent with the TP warming trend (Figure 1c). The dry anomalies over central North China are much smaller in the experiment, but the model does give a region of sinking air in North China (figure not shown). Thus, the overall results suggest that a persistent warming over the TP can lead to a change in EA summer rainfall that is generally similar to the observed trend pattern. The model calculations therefore suggest that the past changes in TP temperatures and EA summer rainfall may be linked. Through what processes could TP warming lead to increased EA subtropical frontal rainfall?

4. Mechanisms by Which TP Warming Influences EA Summer Monsoon

[8] The effects of TP warming are seen both locally and remotely. Locally, the surface warming induces an upward transfer of sensible heat flux in the planetary boundary

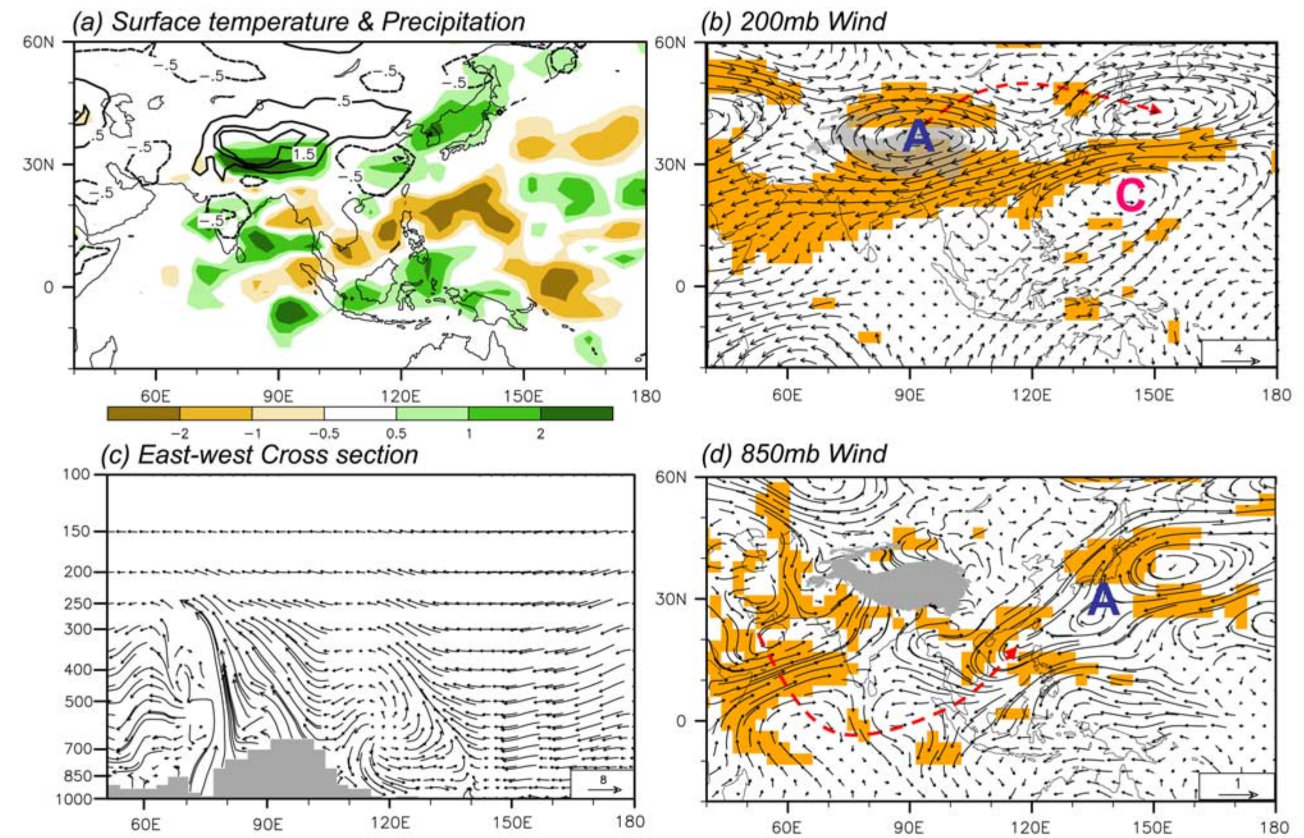

Figure 2. The ensemble mean differences between the warming ("W") and cooling ("C") experiments with the ECHAM4 model in the boreal summer. (a) Surface air temperature (contours in units of °C) and precipitation rate (color shading in units of mm/day, with the green/brown colors meaning enhanced/reduced rainfall). (b) The 200 hPa winds (arrows in units of m/s). (c) Latitude-height cross section of zonal and vertical motion averaged between 28–38°N (zonal motion in units of m/s and vertical motions in units of hPa/day). (d) The 850 hPa winds (arrows in units of m/s). In Figures 2b and 2d, the shading indicates statistically significant at the 95% confidence level based on Student's t-test, the dashed arrows illustrate the Rossby wave trains, and letter A and C denote anticyclonic and cyclonic circulation center, respectively.

layer, which destabilizes the atmosphere and promotes convection, resulting in more precipitation. Meanwhile, the latent heat released in the precipitation leads to ascent and shrinking of air columns above, strengthening the South Asian High in the upper levels [*Rodwell and Hoskins*, 1996] (Figure 2b). Associated with this, both the upper level westerly jet stream to its north and the easterly jet to its south intensify. Accompanying the upward motion over the TP is a notable descent to its northwest and ascent to its northeast (Figure 2c). This east-west asymmetric pattern in vertical motion differs from the classic conceptual model in which descending motion occurs both to the east and to the west of the upward motion over the TP [*Kutzbach et al.*, 1993]. This asymmetric pattern can in part be understood as follows. The diabatic heating in the TP region induces an anticyclone at upper levels and a cyclone at lower levels, and so for hydrostatic balance, the mid-troposphere must become warmer. When this thermal structure is far enough poleward to interact with the southern flank of the mid-latitude westerlies, this air moves down the isentropes on the western side of the TP [*Rodwell and Hoskins*, 1996], but back up on the eastern side.

[9] In the presence of moisture feedback the TP warming-induced ascent to the east of the TP would induce more precipitation over EA. The increased rainfall in EA would favor the strengthening of the EA subtropical front-Subtropical High couplet through the 'Sverdrup' vorticity balance [*Sverdrup*, 1947; *Hoskins and Wang*, 2006]. Previous studies suggested that the 'Sverdrup' vorticity balance can be applied near the ridge of EA subtropical high [*Wu and Liu*, 2003; *Liu et al.*, 2001]. When the precipitation heating is maximized in the mid-troposphere, the air-column stretch-induced vorticity increment in the lower troposphere is accompanied by southerly advection of the smaller planetary vorticity from lower latitudes. The simulated low-level poleward flow between 100°E and 130°E and between about 20°N and 40°N is consistent with this (Figure 2d). Over the Pacific, this flow forms the western flank of the subtropical high centered over Okinawa (Figure 2d). In the subtropical WNP, the low-level anticyclonic center over Okinawa (25°N, 135°E) (Figure 2d) is under an upper-level cyclone (Figure 2b), indicating a baroclinic structure, which confirms that this middle portion of the subtropical high is driven by the latent heating released in the rainfall over the EA subtropical front.

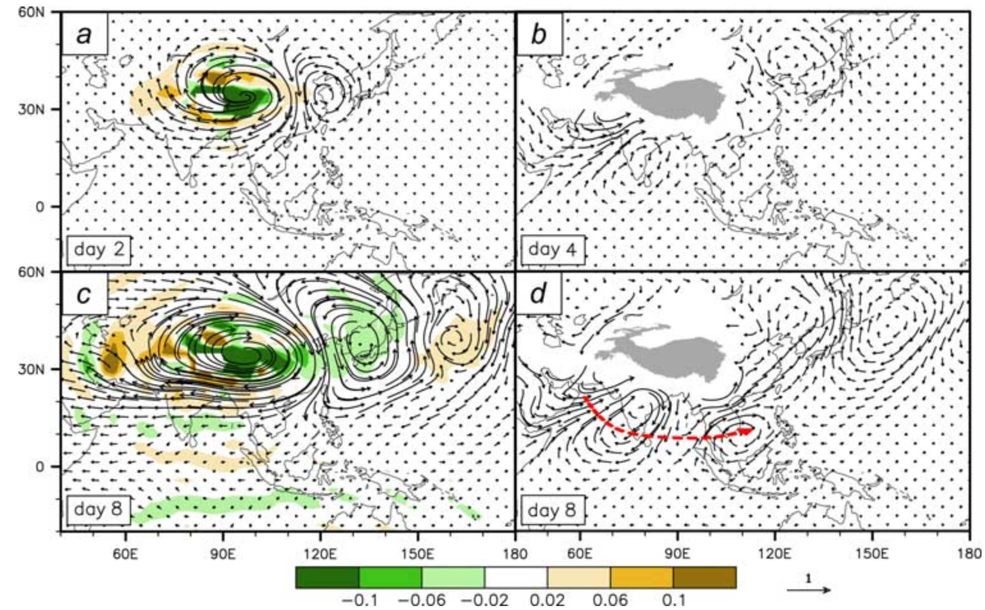

Figure 3. The responses of the circulation anomaly to the initial forcing of the warming Tibetan Plateau: (a) upper winds (m/s) at 200 hPa on day 2, (b) lower winds at 850 hPa on day 4, (c) upper winds on day 8, and (d) lower winds on day 8. The color shading in Figures 3a and 3c denotes 500 hPa vertical motions (green color signifies upward). The response reaches a steady state in about two weeks. The dashed arrow in Figure 3d indicates the low-level Rossby wave train.

[10] The remote impacts of the TP warming are seen from two distinct Rossby wave trains, one in the extratropics that moves along the upper-level westerly jetstream (Figure 2b) and one in the tropics that moves along the low-level monsoon westerly (Figure 2d). Over the WNP, a nearly barotropic anticyclone is found to the east of Japan (Figures 2b and 2d), which is a part of the vorticity wave train originating in the TP (Figure 2b). The low-level anticyclonic ridge over the northern South China Sea is a part of the vorticity wave train along the South Asian monsoon westerly that is excited in the southwest periphery of the TP (Figure 2d). The strengthened low-level anticyclonic circulation over the WNP reinforces the southwesterly along its northwestern flank, increasing water vapor transport toward EA subtropical front and the EA rain belt.

[11] To elucidate how the two wavetrains are generated, we performed further numerical experiments with a dry version of a linearized AGCM, which is developed at the University of Tokyo's Center for Climate System Research [*Watanabe and Kimoto*, 2000]. To clarify the role of dynamic processes, we purposely neglected moist convection. The model was linearized about the climatological June-July-August mean basic state. To mimic the TP warming due to sensible and latent heating in the ECHAM model run, we imposed a heat source over the TP centered at (90°E, 33°N) with an averaged maximum heating rate in the boundary layer being 4°C/day; and above the boundary layer, the heating rate decreases upward exponentially with an e-folding height of about 3 kilometers.

[12] Figure 3 indicates that the development of the extratropical vorticity wave train starts from the upper troposphere, propagating eastward and downward. Since long Rossby waves propagate westward faster than short waves, this wave dispersal generates an upper-level asymmetric anticyclonic circulation with a weak southerly to its west and a strong northerly to its east side (Figure 3a). Thus, cyclonic vorticity develops to the east of the strong northerly, and subsequently a wave train develops along the westerly jetstream around 40°N (Figure 3c). Downward penetration of the response to upper tropospheric potential vorticity anomalies further results in the low-level anticyclone to the east of Japan (Figure 3d).

[13] The development of the low-level wavetrain involves a unique Rossby wave energy propagation in South Asian monsoon, which has not been identified previously. This wavetrain is generated in the region of the northern Arabian Sea (Figure 3b). Due to the strong monsoonal easterly vertical shear (low-level westerly and upper-level easterly), the Rossby wave energy propagation is trapped in the lower troposphere [*Wang and Xie*, 1996]. The wave train has a 4000 km wavelength, consistent with a

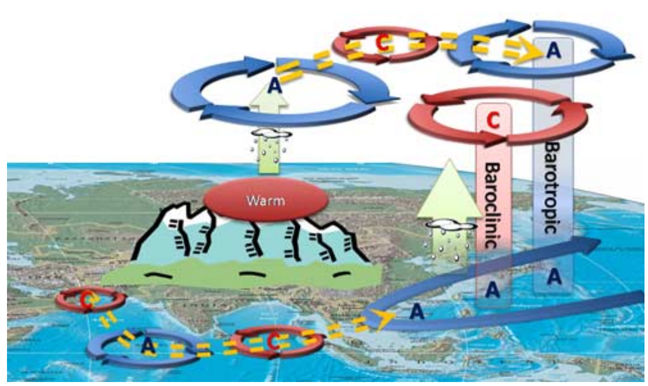

Figure 4. Schematic diagram showing the mechanisms by which the atmosphere responds to the Tibetan Plateau warming, in particular the remote impact of TP warming on East Asian summer monsoon rainfall through two Rossby wavetrains. The letters A and C denote anticyclonic and cyclonic circulation centers, respectively.

stationary Rossby wave on an 8m/s flow. The eastward propagation of this wavetrain induces the anticyclonic anomaly in the South China Sea (Figure 3d). The solution after day 8 has little change with time.

5. Summary

[14] Observational evidence shown here indicates that in the past 50 years the rising temperature over the Tibetan Plateau (about 1.8°C) has a coherent pattern with the trend in the EA rainfall. The model calculations suggest that the past changes in TP temperatures and EA summer rainfall may be physically linked, implying that projected future increases in TP temperatures may lead to further enhanced summer frontal rainfall in EA region.

[15] The mechanism through which the atmosphere responds to the warming TP is illustrated by the schematic diagram shown in Figure 4. The westerly winds rising up the isentropes on the eastern side of the mid-tropospheric warm region give ascent over East China and South Korea (Figure 2c), which results in enhanced rainfall there and enhances the WNP subtropical high centered at Okinawa through heating-induced Sverdrup balance. Meanwhile, two Rossby wave trains are excited due to the TP warming. One has a barotropic structure and propagates downstream along the upper-level westerly jet stream to enhance the anticyclonic circulation to east of Japan. Another wave train developing along the low-level southwesterly monsoon propagates into the South China Sea and enhances the low-level anticyclonic ridge there. The two wave trains deform the WNP subtropical high in such a way that the low-level southwesterly monsoon strengthens moisture transport toward the EA subtropical front and reinforces the precipitation there.

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