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Environ. Res. Lett. **4** (2009) 045203 (8pp) doi:10.1088/1748-9326/4/4/045203

Diurnal variations of summertime precipitation over the Tibetan Plateau in relation to orographically-induced regional circulations

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Received 25 March 2009
Accepted for publication 24 September 2009
Published 23 November 2009
Online at stacks.iop.org/ERL/4/045203

Abstract

The diurnal patterns of variation of summertime precipitation over the Tibetan Plateau were first investigated using the TRMM multi-satellite precipitation analysis product for five summer seasons (i.e. June to August for 2002–2006). Both hourly precipitation amount and precipitation frequency exhibit pronounced daily variability with an overall late-afternoon–evening maximum and a dominant morning minimum. A notable exception is the prevalent nocturnal maximum around the periphery of the Plateau. In terms of the normalized harmonic amplitude, the diurnal signal shows significant regional contrast with the strongest manifestation over the central Plateau and the weakest near the periphery. This remarkable spatial dependence in daily rainfall cycles is clear evidence of orographic and heterogeneous land-surface impacts on convective development.

Using six-hourly NCEP FNL data, we then examined the diurnal variability in the atmospheric circulation and thermodynamics in this region. The results show that the Plateau heats (cools) the overlying atmosphere during the day (night) more than the surrounding areas, and as a consequence a relatively stronger confluent circulation in this region occurs during the day than during the night, consistent with the diurnal rainfall cycles. Moreover, the regions with large low-level convergence and upper-level divergence correspond to the strong diurnal rainfall variations. The reversed daily alterations of convergence–divergence patterns in the vicinity of the Plateau edges are in agreement with the observed nighttime rainfall peak therein. This study further demonstrates the importance of the Tibetan Plateau in regulating regional circulation and precipitation.

Keywords: Tibetan Plateau, diurnal cycle, warm-season precipitation

1. Introduction

The Tibetan Plateau, having an average height of roughly 4 km and an areal coverage of about 2.4 million km^2, is one of the most prominent geographical features on the Earth (figure 1). Because of its unique altitude and horizontal extent, the Plateau is of considerable importance to the Asian monsoon and global general circulation via mechanical and thermal forcing (e.g. Yeh and Gao 1979, Yanai *et al* 1992, Webster *et al* 1998). In the warm season, the Tibetan Plateau is a

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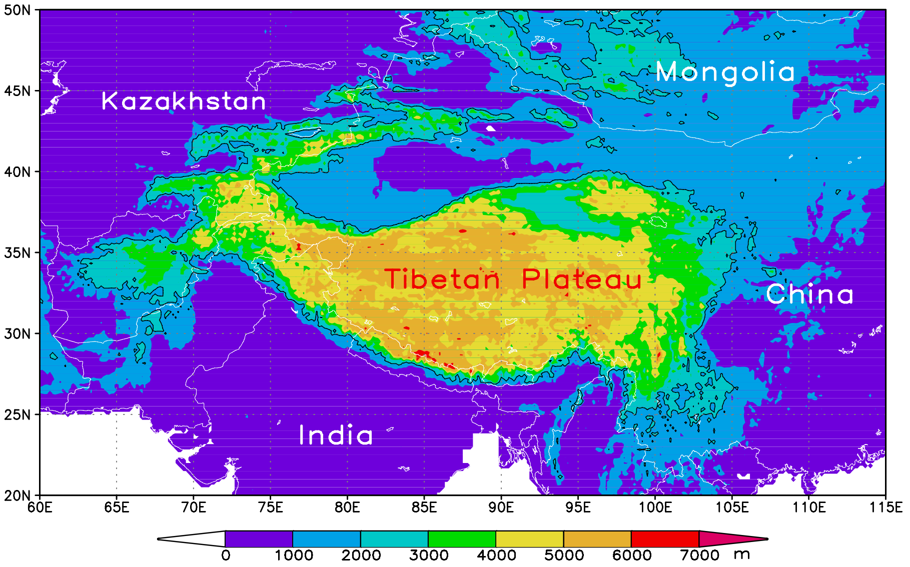

Figure 1. Terrain over the Tibetan Plateau and adjacent areas.

huge elevated heating source that exerts significant influence on atmospheric motions. On average, a heat-low persists in the middle troposphere with a corresponding cyclonic circulation around the Plateau. The spatial distribution of the precipitation anomaly is mostly regulated by variations in the regional circulation of the so-called Plateau monsoon (Tang and Reiter 1984). The salient day–night thermal contrast near the surface strongly affects diurnal variations of regional circulations and convective activity over the wide Plateau (Yeh and Gao 1979, Kuo and Qian 1981).

One of the well-known features of continental convection and precipitation during warm seasons is their significant diurnal variability associated with the well-defined daily solar heating cycle (e.g. Wallace 1975, Liu and Moncrieff 1998, Yang and Slingo 2001, Dai 2001, Carbone *et al* 2002, Nesbitt and Zipser 2003, Yang and Smith 2006). Although a diurnal variation with an afternoon–evening maximum dominates, distinct regional patterns have been documented due primarily to topography, sea–land contrast, surface heterogeneity, and propagating convection. In particular, the elevated heating/cooling associated with orography has been increasingly recognized as one of the most important factors influencing the regionalization of diurnal oscillations. Due to differential elevations between mountains and nearby flat areas (plains), the daytime solar heating or nighttime infrared radiative cooling can generate remarkable horizontal temperature gradients, leading to mountain–plain solenoids and thus diurnal rainfall variations. The complex topography, as well as the substantial inhomogeneity in landscape and landcover on the Tibetan Plateau, may therefore produce some unique regional diurnal rainfall characteristics.

Prominent diurnal variations in various physical fields over the Plateau and its surroundings have been reported in a regional numerical modeling study (Kuo and Qian 1981) and quite a few observational studies using meteorological site data, field observations, radar data and satellite data (e.g. Murakami 1983, Asai *et al* 1998, Ueno 1998, Takagi *et al* 2000, Kuwagata *et al* 2001, Ueno *et al* 2001, Uyeda *et al* 2001, Liu *et al* 2002, Bhatt and Nakamura 2005, Ma *et al* 2005, Fujinami *et al* 2005). There have also been some efforts to simulate the precipitation in this region using regional climate models (e.g. Meinke *et al* 2007, Rockel and Geyer 2008, Dobler and Ahrens 2008), even though the diurnal variability was not addressed in these modeling studies. In spite of these previous studies, the poor time–space sampling and inadequate observations have hampered our efforts at systematically quantifying this fundamental mode of the climate system over the entire Plateau.

This study is intended to document the diurnal characters of summer-season precipitation in the Plateau using a new rainfall dataset with high temporal and spatial resolution. The systematic examination of the diurnal rainfall variation provides a basis for further understanding of orographical and heterogeneous land-surface impacts on convection. Moreover, the diurnal variations of atmospheric circulation and thermodynamics are analyzed to explore their possible correlations with the diurnal variations in precipitation in this region.

2. Data and method

The rainfall data are from the experimental tropical rainfall measuring mission (TRMM) real-time multi-satellite precipitation analysis (Huffman *et al* 2007). The product used is the precipitation estimate from geostationary infrared observations using spatially and temporally varying calibration by the TRMM real-time HQ merged passive microwave precipitation measurements. This dataset has a 0.25° spatial resolution and a 1 h temporal resolution in a global belt from 60°S to 60°N. The present analysis covers five summer seasons (June–August) from 2002 to 2006. These data and the relevant documentation can be obtained at: http://trmm.gsfc.nasa.gov/. The applicability and fidelity of the TRMM rainfall data in

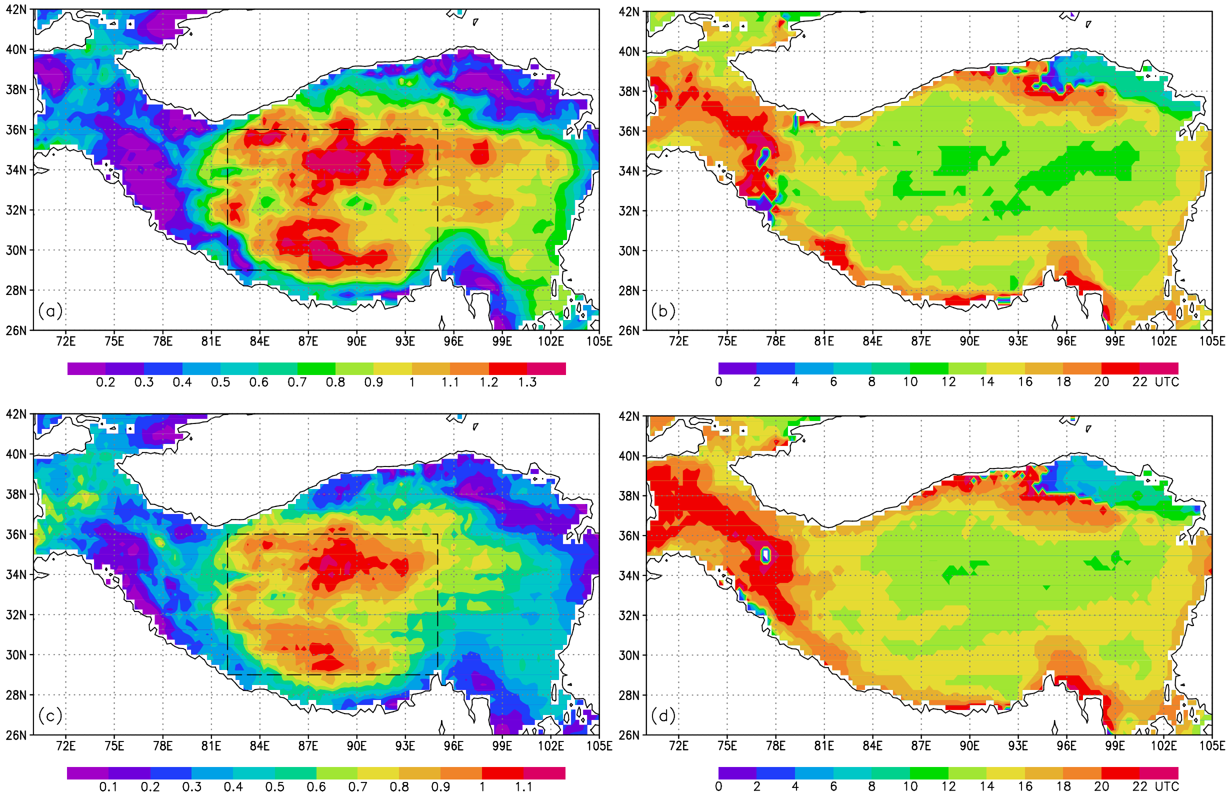

Figure 2. Normalized amplitude (left panels, (a) and (c)) and phase (right panels, (b) and (d)) of diurnal harmonic of hourly rainfall (upper panels, (a) and (b)) and rainfall frequency (lower panels, (c) and (d)). The dark isoline is the 2000 m elevation contour. The dashed box indicates the central Tibetan Plateau.

the Plateau have been quantified by comparison with daily raingauge observations over two sub-domains (Bai *et al* 2008). It was shown that the TRMM product can approximately capture the daily evolution observed from the surface stations, although the intensity is somewhat underestimated, probably because of the sparse meteorological sites which cannot adequately depict the true spatial distributions over the complex mountainous region. Unless otherwise stated, the analysis results in the following presentation represent the averages for five summers. Additional data used include the tropospheric wind, temperature and humidity from the National Centers for Environmental Prediction (NCEP) final global analysis on 1° × 1° grids every 6 h during the same 5 years.

To quantify the diurnal characteristics of amount and frequency of precipitation, we first examined the diurnal composites or averaged daily distributions of hourly accumulated rainfall and frequency during five seasons. We then performed discrete Fourier transforms of the composite hourly time series according to the following formulation (Roy and Balling Jr 2005):

$$R = \bar{R} + \sum_{i=1}^{N/2} A_i \cos\left(\mathrm{i}\frac{2\pi t}{N} - \phi_i\right) \qquad (1)$$

where R and $\bar{R}$ represent either the hourly rainfall amount or frequency and corresponding daily mean, respectively, N is equal to 24, namely the number of total daily observations, A_i and ϕ_i are the amplitude and phase of the ith harmonic mode, respectively, and t stands for the time of day. The calculated amplitude and phase of the first harmonic wave, A_1 and ϕ_1, correspond to the strength of diurnal variability and the timing of the maximum, respectively. Note that the amplitude normalized by the daily-mean value, namely $A_1/\bar{R}$, will be presented in the following to facilitate regional comparisons.

3. Results

3.1. Diurnal variations of precipitation

The normalized amplitude for the diurnal harmonic of hourly rainfall in figure 2(a) indicates remarkable daily variability in the amount of precipitation over the Tibetan Plateau, with the strongest signal in the central Plateau and the weakest signal around the Plateau periphery. As shown later, these spatial differences are consistent with the regional diurnal patterns in the large-scale circulations. The corresponding phase (Coordinated Universal Time (UTC) hours for the maximum) in figure 2(b) shows that almost the entire Plateau rainfall preferentially occurs between 10:00 and 14:00 UTC, equivalent to afternoon–evening local solar time (LST) in the Plateau. This late afternoon–evening preference for convective activity in the majority of the Plateau is similar to many previous studies of diurnal variations in precipitation in other continental regions (e.g. Wallace 1975, Yang and Slingo 2001, Dai 2001, Carbone *et al* 2002) and is generally attributed to the cumulative daytime solar heating over the land surface. An exceptional case is the nocturnal maximum during 18:00–24:00 UTC (00:00-06:00 LST) in the far western Plateau and the neighborhood of the southern and northern edges. This unique pattern is possibly associated with local thermally-forced wind systems. At night the strong radiative cooling over elevated terrain relative to adjacent areas produces downslope pressure gradients and accordingly ridge-to-valley breezes which can initiate nocturnal convection. Due to the extremely steep slopes along the Plateau periphery, the mountain flows could be more significant as compared to other mountainous locations and cause the nocturnal precipitation maximum therein.

The diurnal patterns of rainfall frequency (figures 2(c) and (d)) are largely comparable to the amount of rainfall in both the amplitude and the phase. On average, the frequency amplitude is slightly weaker than the counterpart of rainfall amount, suggesting that not only is frequency enhanced in the evening, but also the intensity for each individual event. In addition, the frequency peaks roughly 1–2 h behind the rainfall amount, but this phase contrast is not visible in the actual timing of the maximum (see below).

Figure 3(a) presents the diurnal composite results spatially averaged over the central Tibetan Plateau (82°–95°E, 29°–36°N). It is readily seen that rainfall amount and frequency share a common pattern of evolution with striking diurnal variations, characteristic of a minimum around 04:00 UTC (mid-morning), subsequent rapid intensification, a maximum around 12:00 UTC (late afternoon), and steady weakening throughout the night. The two quantities attain their respective extremum almost simultaneously, but the variation in the amount of rainfall is slightly larger than the frequency variation. Note that although they are roughly in phase in terms of the extreme values, the frequency distribution has a heavier tail than the amount, indicative of numerous light showers from weak and less-organized convection during the night. In addition, the simultaneous occurrence of their respective maximum is distinct from the 1–2 h phase shift in the first harmonics discussed above. Careful inspection reveals that the later timing of the frequency peak for the diurnal harmonic is attributed to the heavy tail in the frequency curve. Figure 3(b) shows the statistical results of the maximum timing, namely the percentage of grid points with different UTC hours for peak rainfall amount or frequency. There is a late-afternoon–evening preference in this region, consistent with the diurnal behavior of the domain-averaged rainfall (figure 3(a)). For example, as much as 27% (28%) of grids attain the maximum in hourly accumulated rainfall (frequency) at 12:00 UTC, and more than 82% (84%) grid cells reach the peak rainfall intensity (frequency) between 10:00 and 14:00 UTC. Therefore, the daily rainfall peak is phase-locked with its diurnal cycle.

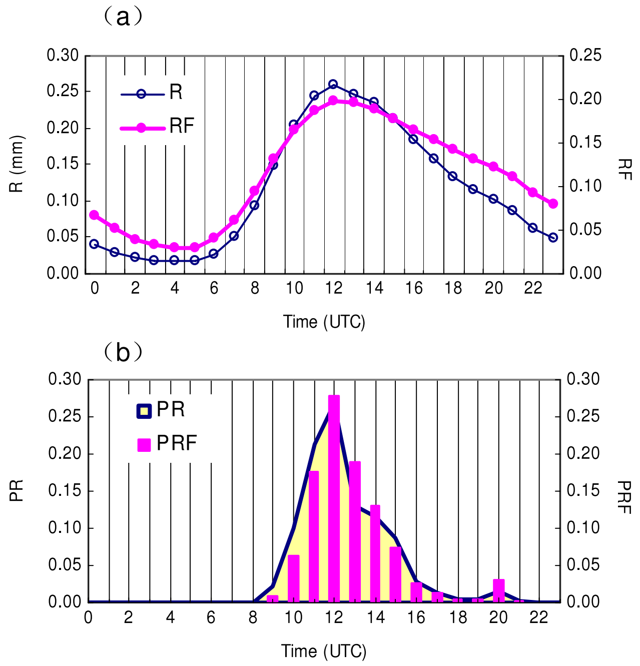

Figure 3. (a) Diurnal cycle of rainfall (R) and rainfall frequency (RF) averaged over the central Plateau. (b) Percentage of grids with various UTC hours of maximum hourly rainfall (PR) and rainfall frequency (PRF) with respect to total grids in the central Plateau.

3.2. *Diurnal features in the regional circulation*

Significant diurnal variations are present in the regional circulation over the Plateau and adjacent areas. Figure 4 displays the lower-tropospheric wind field at 600 hPa, which is the standard pressure level closest to the Plateau surface and therefore strongly modulated by the daily solar forcing and underlying large-scale orography. In the summer daily-mean wind field (figure 4(a)), westerly (southerly) winds prevail north (south) of the Plateau. For the most part, northerly and southerly flows prevail in the northern and southern Plateau, respectively, generating an approximately zonally oriented convergence zone. The differential streamline field (figure 4(b)) indicates much greater confluence or convergence at 12:00 than at 00:00 UTC except in the neighborhood of surrounding edges. This morning–evening contrast in the lower-level circulations supports more intense convective activity during the evening hours than the morning hours in most geographical areas. There is an opposite diurnal pattern along the boundaries. Furthermore, the dual marked confluent centers in the differential field are in good correspondence with the largest diurnal oscillations identified in the rainfall amount and frequency (figures 2(a) and (c)). At the upper troposphere (250 hPa), strong divergence dominates in the summertime, with the maximum centered in the central Plateau (figure 4(c)). Moreover, the late-afternoon divergence is much larger than in the early morning, and this temporal contrast is especially significant in the central part of the Plateau (figure 4(d)). An opposite, albeit much weaker, evening–morning differential divergence appears in the neighboring areas.

Taken together, the lower-level convergence or cyclonic flow and upper-level divergence or anticyclonic flow are favorable to summertime convection in the Plateau, whereas their evening enhancement and morning reduction are largely consistent with the daily rainfall cycle discussed above. In contrast, the reversed daily variations of divergence–

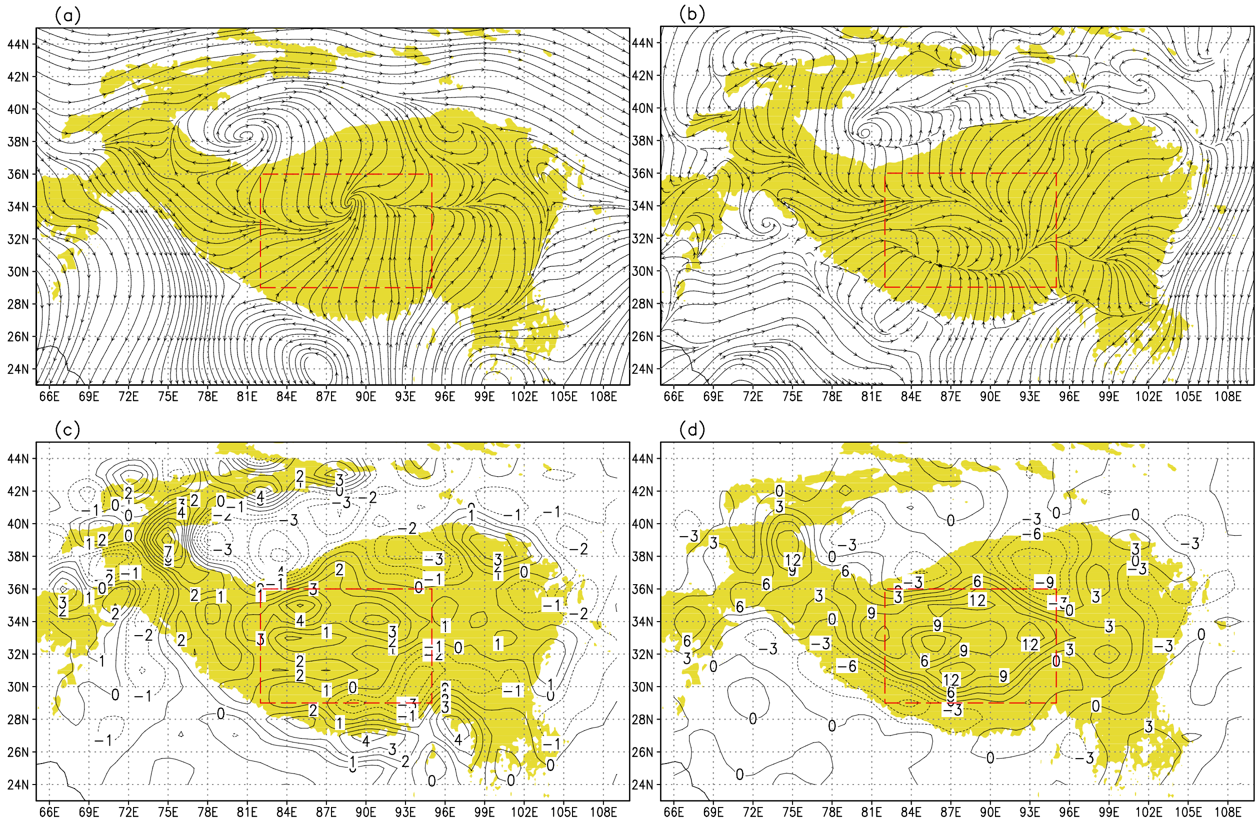

Figure 4. (a) Daily-mean 600 hPa streamline field; (b) differential 600 hPa streamline field between 12:00 and 00:00 UTC (12 minus 00 UTC); (c) daily-mean 250 hPa divergence field (10^{-6} s^{-1}); and (d) differential 250 hPa divergence between 12 and 00 UTC (10^{-6} s^{-1}). The shading represents regions of an elevation above 2000 m.

convergence flows near the periphery agree with the nocturnal preference for rainfall. On the other hand, however, the observed diurnal behavior in large-scale circulations could be significantly affected by the diurnal cycle in convection through two-way interactions, especially the upper-tropospheric flow which cannot be much affected by the daily alteration of the low-level thermodynamics in response to the radiative heating cycle over land surfaces.

3.3. *Diurnal features in vertical velocity*

As expected, vertical motions undergo apparent day–night alterations in correspondence with the horizontal circulation. Figure 5 presents the vertical velocity along a latitude-height cross section averaged over the meridional belt of 82°–95°E. The daily-mean field (figure 5(a)) shows widespread deep ascending motions over the whole Plateau and also the adjacent lowland south of the Plateau and descending motions north of ∼40°N. This upward–downward motion pattern is generally consistent with the climatological summer-season rainfall distributions. Note that the relatively shallow upward motions along the northern and southern slope are the likely result of thermally-driven mountain–plain solenoids and/or mechanical forcing. Solenoidal circulations or mountain-valley breezes and their role in the daily-repeating regeneration of warm-season precipitating systems have been well-documented in many other mountainous regions and studied both observationally and numerically (e.g. Banta and Cotton 1981, Banta 1984, Wolyn and Mckee 1994, Tripoli and Cotton 1989, Stewart *et al* 2002). The comparatively stronger ascending velocity in the local evening (figure 5(b)) is well-coupled with the aforementioned diurnal oscillations in the divergence–convergence field and precipitation and also is qualitatively comparable to modeling results by Kuo and Qian (1981).

3.4. *Diurnal features in specific humidity*

Clear signals of diurnal variation occur in the moisture field. The daily-mean specific humidity (figure 5(c)) consistently decreases from low to high latitudes, and orographic blocking leads to the huge differences between the southern and northern slopes. The enhanced late-day tropospheric humidity (figure 5(d)) is attributed to the cumulative impact of increased daytime surface water vapor fluxes and convective transport from the planetary boundary layer toward the upper atmosphere, and in turn it would have a positive feedback on convective development and rainfall production in the afternoon–evening hours.

3.5. *Diurnal variations in near-surface air temperature*

The 600 hPa temperature in figure 6 exemplifies the evident diurnal cycle of low-level thermodynamics. In terms of the

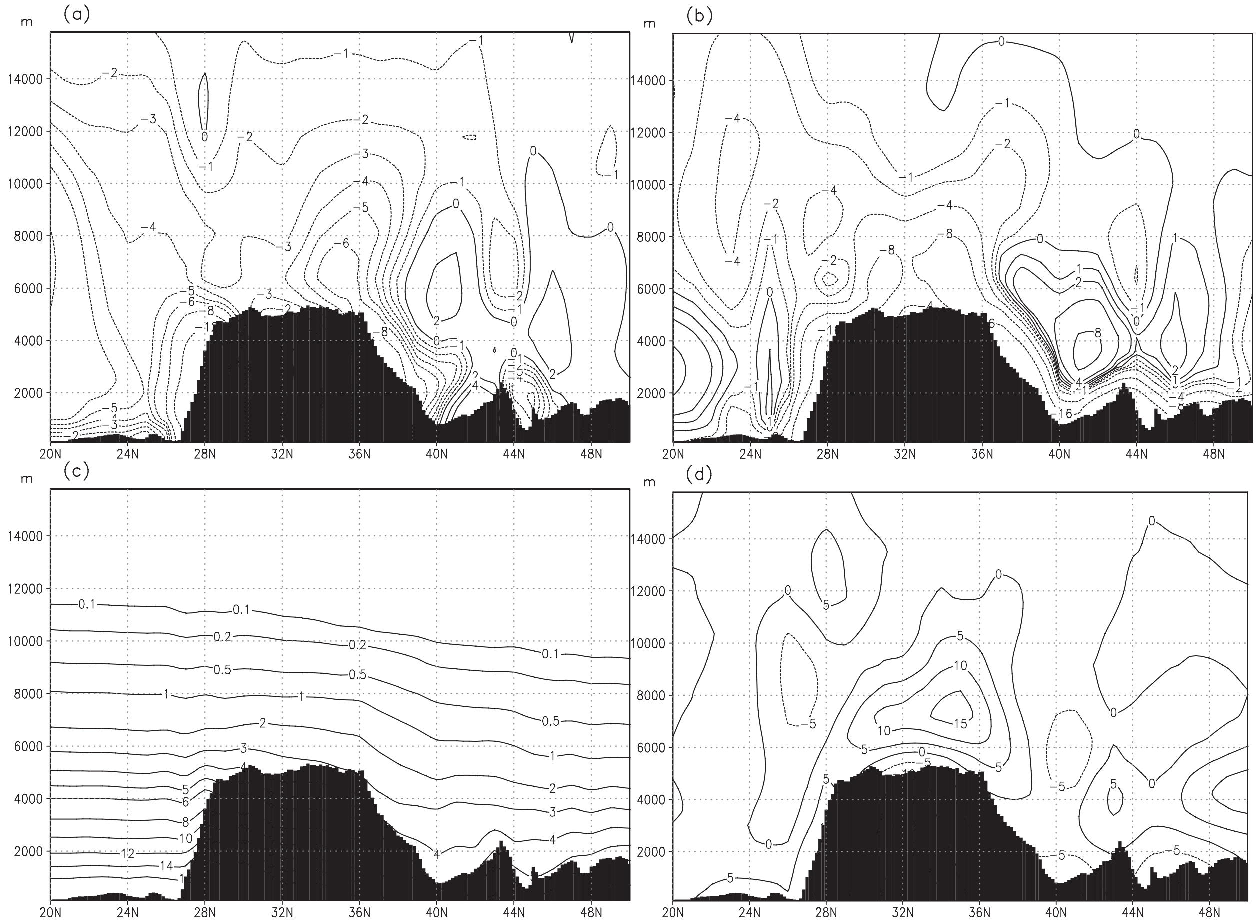

Figure 5. Latitude–height cross section averaged over the meridional belt of 82°–95°E for: (a) daily-mean vertical velocity (mbar day^{-1}); (b) differential vertical velocity between 12 and 00 UTC (12 minus 00 UTC); (c) daily-mean specific humidity (g kg^{-1}); and (d) differential specific humidity between 12 and 00 UTC (per cent relative to daily mean). The shading indicates orography.

daily-mean temperature (figure 6(a)), the Plateau is warmer than the surrounding regions, consistent with the notion that the Tibetan Plateau is an elevated heat source during the summer season. The warmest center is located in the central southern Plateau with a highest value of more than 11 °C. As expected, the temperature in the evening is much warmer than in the early morning (figure 6(b)), and the corresponding difference reaches more than 6 °C in the core portion of the Plateau. These diurnal variation ranges are generally comparable to previously simulated and station-observed results (Kuo and Qian 1981). As well as the day–night alteration of the low-level thermodynamics in response to the radiative heating cycle over the land surfaces, the local mountain–valley circulation and the regional mountain–plain solenoidal circulation in association with elevated-heating-induced horizontal thermal gradients further enhance the diurnal rainfall variations in the Plateau. Therefore, there exists a causal relationship between diurnal variations of rainfall and orographically-induced regional circulation in the summer.

4. Summary

The unique height and horizontal extent of the Tibetan Plateau as well as the complex landscape create a rich variety of unique, yet unknown, precipitation variabilities. Herein we investigated the diurnal features of rainfall over the Tibetan Plateau using a new TRMM dataset and associated large-scale thermodynamics and circulations. The major findings are as follows.

- Strong diurnal oscillation is present in both amount and frequency of precipitation over the Plateau and exhibits large spatial variabilities. For the most part, the most significant signal is present over the central Plateau on the basis of normalized harmonic amplitudes, with two regional centers coupled with local anomalous day–night differential confluent flows at low levels. In comparison, the manifestation is much weaker in the western part of the Plateau as well as near the surrounding edges. The large spatial variations reveal the importance of the complex terrains and landcover in modulating regional precipitation.
- Diurnal variations are broadly characterized by a late-afternoon–evening maximum and a morning minimum in most regions, in phase with the accumulative solar heating near the surface. This is generally similar to the diurnal phasing documented in other continental regions. An apparent exception appears around the Plateau edges where a nocturnal maximum and an afternoon minimum

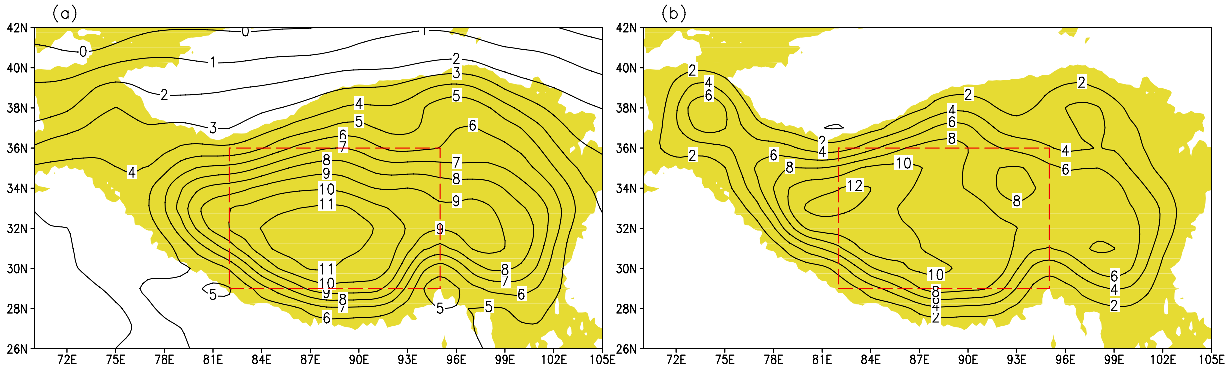

Figure 6. (a) Daily-mean 600 hPa temperature (°C) and (b) differential 600 hPa temperature between 12:00 and 00:00 UTC (12 minus 00 UTC). The shaded areas are above 2000 m.

prevail. This phenomenon is possibly linked to the peripheral steep topography which is favorable for the generation of strong local mountain–valley breezes.

- Diurnal variations in regional circulations and thermodynamic fields consistently correspond to the diurnal rainfall cycles. In particular, the low-level convergent and upper-level divergent areas in the evening–morning differential streamline field are coupled with the large diurnal rainfall signals, whereas the opposite day–night divergence–convergence contrast near the Plateau edges is consistent with the observed nocturnal rainfall maximum therein. The underlying dynamical processes associated with their causal relationships will be explored by ongoing cloud-resolving numerical modeling. In particular, the physical mechanisms behind the prevailing nighttime convection in the peripheral areas will be thoroughly investigated.

Acknowledgments

This work was jointly supported by the Special Fund for Nonprofit Industry (GYHY200706029), National Basic Research Program of China (2010CB833406) and Natural Science Foundation of China (40825008). We are appreciative of the comments on the manuscript by Mitch Moncrieff, James Done, John Tuttle and two anonymous reviewers.

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