The mass elevation effect of the Tibetan Plateau and its implications for Alpine treelines

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ABSTRACT: The immense and towering Tibetan Plateau (TP) acts as a heating source and shapes the climate of not only the Eurasian continent but also the entire world. The mass elevation effect of the TP was first observed in the 1950s; however, due to the scarcity of meteorological observation stations and limited climatic data, little information on the mass elevation effect of the plateau and its implications for the position of Alpine treelines in the southeastern part of the TP is quantitatively known. This paper compares monthly mean air temperature differences at elevations of 4000, 4500, 5000, 5500 and 6000 m between the main plateau, the Qilian Mts. in the northeastern corner of the plateau and the Sichuan Basin to the east of the plateau to quantify the mass elevation effect of the plateau. The TP air temperature data are retrieved from Terra moderate-resolution imaging spectroradiometer (MODIS) land surface temperature (LST), and the free-air temperatures over the westernmost Sichuan Basin are estimated using the measured lapse rate from Mt. Emei, which is located in the western portion of the Sichuan Basin. The results demonstrate the following important characteristics. (1) Owing to the mass elevation effect, air temperatures gradually increase from the eastern edge to the interior main TP. The monthly mean air temperature in the interior main plateau is approximately 2–7 °C higher than in the surrounding mountains and adjacent lowland areas. At an elevation of 4500 m (corresponding to the mean altitude of the TP), the monthly mean temperature differences between the plateau and the Sichuan Basin range from 3.58 °C (April) to 6.63 °C (June); the monthly temperature differences between the plateau and the Qilian Mts. range from 1.6 °C (July) to 7.7 °C (March). (2) The mass elevation effect of the plateau pushes the 10 °C isotherm upward in the warmest month and is indicative of a warmth index of 15 °C month up to elevations of 4600–4700 m, which enables the treeline altitude in the interior TP 500–1000 m higher than along the eastern edge. Therefore, mass elevation effect contributes to the occurrence of the highest treeline in the Northern Hemisphere, which is present on the southeastern TP.

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1. Introduction

One of the most important properties of the immense and towering Tibetan Plateau (TP) is that it thermodynamically shapes the climate of not only the Eurasian continent but also the entire world. The TP has even evolved unique geographical and ecological patterns. In the southeast region, the Alpine tree line climbs upward to approximately 4600–4700 m (Troll 1973; Zheng and Li, 1990) and even higher (4900 m) on a few sunny slopes (Miche et al., 2007), which represents the highest treeline in the Northern Hemisphere, extending approximately 1000 m higher than the treeline in the surrounding areas. This results from the so-called mass elevation effect of the TP (Holtmeier, 2003; Han et al., 2012) or Massenerhebungseffekt (De Quervain, 1904), which accounts for the observed tendencies in temperature-related parameters, such as treeline and snowline, to occur at higher elevations in the Central Alps compared to their outer regions (De Quervain, 1904; Schroeter, 1908). This phenomenon has also been discovered and reported in other places around the world (Leuschner, 1996; Holtmeier, 2003; Flenley, 2007; Barry, 2008).

Many studies have attempted to explain this phenomenon from different perspectives. Grubb (1971) stated that the high frequency of fog in tropical mountainous regions reduced the nutritive materials in soil and restrained the growth of vegetation on mountains in the tropics. Therefore, there is a tendency for physiognomically and sometimes floristically similar vegetation types to appear at lower altitudes on tropical mountains. Tollner (1949) argued that large mountain massifs have a positive effect on the altitudinal position of the timberline because they serve as a heating surface that absorbs solar radiation and transforms the radiation into longwave energy. Consequently, the air temperatures of these large mountain massifs are typically higher compared to the surrounding free atmosphere at same elevations (Holtmeier, 2003; Han et al., 2012). Flohn (1953, 1968) proposed that elevated plateau surfaces, such as the TP and the Altiplanos in
South America, are warmer than the adjacent free air in summer due to the increase in incident solar radiation with altitude and the substantial longwave radiation at higher elevations. This hypothesis was confirmed by later studies (Yeh, 1982; Chen et al., 1985). Moreover, Barry (2008) and Holtmeier (2003) noted that the longer and warmer growing season at all elevations make the treeline in the Central Alps approximately 400 m higher than in the outer ranges. The mass elevation effect has been widely applied in ecological studies; normally it was called as the heating effect in meteorological studies (Holtmeier, 2003; Barry, 2008).

In fact, the heating effects on Eurasian weather and climate and on the atmospheric general circulation have been studied in climatology for many years (Yeh, 1982; Yeh and Wu, 1998; Yanai and Wu, 2006; Yeh and Chang, 1974; Chen et al., 1985; Wu et al., 1997). It was initially discovered that the TP is a summertime atmospheric heat source in the 1950s (Flohn, 1957; Yeh et al., 1957), subsequently many studies were focused on the sensible and latent heat fluxes on the TP. Yeh (1982) indicated that the total energy flux from the plateau to the atmosphere was 231 W m$^{-2}$ in June. Various estimates have suggested that the heating rate is approximately 2°C day$^{-1}$ over the eastern half of the plateau (Chen et al., 1985). Such substantial heating must have large effects not only the climate of the TP but also the ecological patterns on the plateau, especially the spatial pattern of the mountain altitude belts (Zheng and Li, 1990; Liu et al., 2003). For example, the highest treeline and snowline in the Northern Hemisphere occur on the TP. However, due to the scarcity of meteorological observation stations and limited climatic data, previous studies on the heating effect have focused on the heat exchange between the plateau and surrounding areas; and little is quantitatively known about the detailed implications of the heating effect (mass elevation effect) for the TP ecological patterns. Moreover, the extent of the mass elevation effect of the TP and the extent of warming on the main plateau relative to the surrounding areas remain unknown. Thus, this paper attempts to quantify the mass elevation effect by comparing the air temperature difference between the main plateau and the surrounding mountains/adjacent lowlands at specified elevations and to discuss the implications of the mass elevation effect on the occurrence of the highest treeline in the Northern Hemisphere, which occurs in the southeastern region of the TP.

2. Study area

The study area is located between latitudes 25–40°N and longitudes 75–105°E (Figure 1), including the entire TP and adjacent areas. The plateau covers an area of nearly 2.5 million km$^2$, most of which is between 4000 and 6000 m above sea level (asl). The Himalayan, Hengduan and Kunlun Mountains are situated on the southern, eastern and northern borders of the plateau, respectively. The Gangdisè and Tanggula Mountains lie in the internal main plateau and divide the main plateau into three parts (i.e. the southern, central and northern main plateau). The Qaidam Basin, located in the northeast region of the TP, is approximately only 3000 m asl and separates the Qilian Mts. from the main plateau. We selected the Qilian Mts. and the Sichuan Basin (<1000 m asl) to the east of the plateau for air temperature comparisons.

3. Data and data sources

3.1. Air temperature data

The air temperatures are estimated based on the MODIS land surface temperature (LST) data, meteorological data for 2001–2007 from 137 stations and the ASTER GDEM data (Yao and Zhang, 2013). The MODIS LST data from 2001 to 2007 were obtained from the Terra Monthly Land
Surface Temperature/Emissivity (MOD11C3) product at 0.05° geographic Climate Modeling Grid (CMG) spatial resolution and downloaded from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/lpdaac/products/modis_products_table). The air temperatures were estimated using ArcGIS with geographical weighted regression (GWR) methods; the root mean square error (RMSE) for every month was relatively small, ranging from 1.13 °C for August to 1.53 °C for March. These estimate data are spatially continuous and contain more detailed air temperature information than the observed data, which are scattered. The spatial resolution of the estimated air temperature data is 0.05° geographic CMG.

3.2. ASTER GDEM data
ASTER Global Digital Elevation Model (GDEM) data with a spatial resolution of 30 m were downloaded from http://www.gdem.aster.ersdac.or.jp/download.jsp. The dataset contained a few missing values; these points were replaced with the mean of the adjacent $3 \times 3$ pixels.

3.3. Treeline data
We collected a total of 166 treeline data points that encompass the entire TP from the available literatures (Appendix). For each data site, the geographic coordinates (latitude and longitude) were extracted from the corresponding study or a map; the air temperatures at the treeline sites were subsequently acquired from the estimated temperature data.

4. Methods
First, air temperature data had been estimated by the GWR method based on time series of MODIS LST data, together with meteorological data of 137 stations for 2001–2007 and ASTER GDEM data (Yao and Zhang, 2013):

$$T_i(u) = \beta_0(u) + \beta_1(u)T_S(u) + \beta_2(u)h_i(u)$$

(1)

where $T$ is air temperature, $T_S$ is MODIS LST, $u$ is a certain spatial location for air temperature estimation, and $i$ is the number of spatial locations; $h$ is the altitude acquired from ASTER GDEM. Using GWR, $T$ at every location in the study area can be estimated from MODIS LST and altitude at that location (Equation (1)). Coefficient surfaces of MODIS LST, altitude and constant are generated separately, and then the estimation model for air temperature on the whole TP can be developed.

Then, to determine the relative extent of the mass elevation effect of the main plateau, monthly mean air temperatures at similar elevations and latitudes over the TP and over the neighbouring areas were compared. Air temperatures were calculated at altitudes of 4000, 4500, 5000, 5500 and 6000 m for both the main plateau and the Qilian Mts. The altitudes were determined from the ASTER GDEM dataset. The temperatures at elevations of 4000–6000 m in the Hengduan Mts. and in the southern and the central main plateau can be found in supporting Tables S1–S3. For the Sichuan Basin, the monthly mean air temperatures were adjusted to higher altitudes using the following equation:

$$T_{\text{adjusted}} = T + (h - H) \times \partial$$

(2)

where $\partial$ is the lapse rate, $T$ is the air temperature at a height $h$ and $T_{\text{adjusted}}$ is the adjusted air temperature at an elevation $H$. Few lapse rates have been reported in the Sichuan Basin, especially in the western portion of the basin. Liu (1992) measured the air temperatures on the top and piedmont of Mt. Emei and reported that the monthly lapse rates varied from 0.49 °C 100 m$^{-1}$ in December to 0.60 °C 100 m$^{-1}$ in May (Table 1). Mt. Emei is located on the southwestern edge of the Sichuan Basin and on the southeastern edge of the Hengduan Mountains. Wu (1996) measured the air temperature on Mt. Qingcheng and reported a lapse rate of 0.56 °C 100 m$^{-1}$ in June. Zheng et al. (1986) reported that the lapse rates in the Wolong Nature Reserve (Mt. Balang) ranged from 0.42 °C 100 m$^{-1}$ in January to 0.50 °C 100 m$^{-1}$ in August. Mt. Qingcheng and Mt. Balang are located in the transition region of the basin and the easternmost region of the plateau; however, the Wolong Nature Reserve is closer to the main plateau than to the Sichuan Basin. These previous studies suggest that the lapse rates in the western Sichuan Basin are small in winter (0.42–0.53 °C 100 m$^{-1}$) and large in summer (0.55–0.60 °C 100 m$^{-1}$). Li and Xie (2006) analyzed the spatial distribution of lapse rates on the TP using an interpolation method and reported that the lapse rates decreased from 0.7 °C 100 m$^{-1}$ in the northwest to 0.45–0.50 °C 100 m$^{-1}$ in the southeast. According to these previous studies, the lapse rates in the western Sichuan Basin should be between 0.42 and 0.60 °C 100 m$^{-1}$. However, the interpolated results may contain some uncertainty. Therefore, we believe that the lapse rates measured on Mt. Emei are more creditable; these lapse rates were selected for the air temperature adjustment calculations.

Table 1. Reported lapse rates west of the Sichuan Basin (units: °C 100 m$^{-1}$).

| Mountains  | January | February | March | April | May  | June | July | August | September | October | November | December |
|-----------|---------|----------|-------|-------|------|------|------|--------|-----------|---------|----------|----------|
| Mt. Emei  | 0.51    | 0.53     | 0.56  | 0.57  | 0.60 | 0.60 | 0.55 | 0.56   | 0.54      | 0.53    | 0.55     | 0.49     |
| Mt. Qingcheng | 0.56    |          |       |       |      |      |      |        |           |         |          |          |
| Mt. Balang | 0.42    |          |       |       |      |      |      |        |           |         |          | 0.50     |

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To reveal air temperature variation from the periphery to the interior of the plateau, we carried out air temperature comparison between the main plateau and the transition region and the adjacent lowland areas at the same latitude. Mt. Emei and Mt. Qingcheng were chosen as mountains in the transition region; four locations on the main plateau at the same latitude were chosen for comparison. The air temperatures on Mt. Emei and Mt. Qingcheng were adjusted to the altitudes of the four locations on the main plateau using Equation (2); the measured lapse rates that were used for adjustments are listed in Table 1. The four locations on the main plateau are shown in Figure 1; their corresponding altitudes are listed in Tables 3 and 4.

We subsequently calculated the altitude of the warmest month 10°C isotherm and the warmth index at 4500m (which corresponds to the mean elevation of the main plateau) based on the estimated monthly mean air temperatures and the ASTER GDEM data. Previous studies have shown that altitudes corresponding to the warmest month 10°C isotherm and the warmth index of 15°C month (the summation is performed for months in which the monthly mean air temperature is greater than 5°C) exhibit the best overall occurrence of forest limits (Troll, 1973; Ohsawa, 1990). Therefore, the potential altitude of Alpine treelines can be estimated using the 10°C isotherm in the warmest month and a warmth index of 15°C month. The 10°C isotherms were extracted from the estimated air temperature data; the corresponding altitudes were obtained from the ASTER GDEM data using ArcGIS. The warmth index (WI) at the mean elevation of the main plateau (4500 m asl) is calculated as follows:

$$ WI = \sum (t - 5) $$

Here, $t$ is the monthly mean air temperature at 4500 m asl and WI is the sum of $t - 5$ for months in which $t$ exceeds 5°C (Kira, 1948; Ohsawa, 1990).

Lastly, to further evaluate the implications of the mass elevation effect on Alpine treelines, the correlation between the mass elevation effect and the treeline position is analyzed.

5. Results

5.1. The air temperature on the main plateau is higher than over the surrounding mountains and neighbouring lowland at the specified elevations

The air temperature at a specific elevation is higher on the main plateau than in the Sichuan Basin not only in summer but also throughout the entire year (Figure 2 and Table 2). At 4500 m asl, the temperature difference between the southern plateau and the Sichuan Basin is 5.25°C for the coldest month (January) and 4.86°C for the warmest month (July); the minimum and maximum differences are 3.58°C (April) and 6.63°C (June), respectively (Figure 3(a)). The temperature differences increase with altitude in all months. From 4000 to 6000 m, the temperature difference between the southern plateau and the Sichuan Basin increases from 4.17 to 6.41°C in January and from 3.21 to 8.32°C in July; between the Hengduan Mts. and the Sichuan Basin, the temperature difference increases from 5.2 to 8.16°C in January and from 3.33 to 9.08°C in July (Figure 3(b)). This result demonstrates that the air temperature on the main plateau is higher than over the adjacent lowland area and that the difference increases with increasing elevation.

A comparison of air temperatures between the central main plateau and the Qilian Mts. also suggests that temperatures on the main plateau are higher than over the surrounding mountains (Figure 4 and Table 2). At an elevation of 4500 m, the temperature difference between the central main plateau and the Qilian Mts. is 6.61°C in the coldest month (January) and 1.62°C in the warmest month (July); the minimum and maximum differences are 1.62°C (July) and 7.7°C (March), respectively. Moreover, between the northern main plateau and the Qilian Mts., the minimum monthly air temperature difference is 0.5°C (July) and the maximum difference is 4.9°C (December). The temperature differences between the central main plateau and the Qilian Mts. are small (<3°C) in warm months (May through September) and large (3–9°C) in cold months (October to April) (Figure 5). However, between the southern main plateau and the Sichuan Basin,
Table 2. Monthly temperatures and temperature differences (ΔT) between the main plateau and the surrounding/adjacent lowland areas at an altitude of 4500 m (units: °C).

|           | January | February | March | April | May | June | July | August | September | October | November | December |
|-----------|---------|----------|-------|-------|-----|------|------|--------|------------|---------|----------|----------|
| Main plateau | −10.19  | −8.16   | −4.73 | −0.1  | 3.77| 7.83 | 9.94 | 9.59   | 6.9        | 0.13    | −6.3     | −9.14    |
| Hengduan Ms. | −7.07   | −5.28   | −2.27 | 0.83  | 5.21| 8.2  | 10.08| 9.93   | 7.2        | 2.12    | −3.84    | −6.52    |
| Southern main TP | −7.55   | −6.08   | −2.85 | 0.83  | 4.42| 8.5  | 10.22| 9.89   | 7.5        | 2       | −3.6     | −6.4     |
| Central main TP | −10.8   | −8.26   | −4.41 | 0.21  | 4.02| 8.45 | 10.56| 10.11  | 7.39       | 0.49    | −6.22    | −9.56    |
| Northern main TP | −13.48  | −11.17  | −7.58 | −1.37 | 3.01| 6.95 | 9.44 | 9.00   | 6.16       | −2.41   | −9.55    | −12.31   |
| Qilian Ms. | −17.41  | −15.58  | −12.08| −4.19 | 2.11| 6.13 | 8.94 | 7.93   | 4.4        | −5.44   | −13.08   | −17.16   |
| Sichuan Basin | −12.8   | −10.29  | −7.16 | −2.75 | −0.41| 1.87 | 5.36 | 4.15   | 1.54       | −2.23   | −7.63    | −10.94   |
| ΔT Hengduan-Sichuan | 5.73    | 5.01    | 4.89 | 3.58  | 5.62| 6.33 | 4.72 | 5.78   | 5.66       | 4.35    | 3.79     | 4.42     |
| ΔT Southern main-Sichuan | 5.25    | 4.21    | 4.31 | 3.58  | 4.83| 6.63 | 4.86 | 5.74   | 5.96       | 4.23    | 4.03     | 4.54     |
| ΔT Central main-Qilian | 6.61    | 7.32    | 7.67 | 4.4   | 1.91| 2.32 | 1.62 | 2.18   | 2.99       | 5.93    | 6.86     | 7.60     |
| ΔT Northern main-Qilian | 3.93    | 4.41    | 4.5  | 2.82  | 0.9 | 0.82 | 0.5  | 1.07   | 1.76       | 3.03    | 3.53     | 4.85     |

Figure 3. (a) Monthly temperature differences at an elevation of 4500 m and (b) temperature differences as a function of altitude between the southern main plateau/the Hengduan Ms. and the Sichuan Basin.

the air temperature differences are largest in the warm months (>4 °C) (Figures 3 and 5). Furthermore, the air temperature differences increase with altitude from 4000 to 5000 m and then decrease with altitude from 5000 to 5500 m (Figure 5(b)).

5.2. Air temperatures gradual increase from the easternmost to the interior plateau

To further reveal the mass elevation effect of the TP, air temperatures in Mt. Emei and Mt. Qingcheng, are compared with those over the main plateau at the same latitudes and altitudes (Table 3). In July, the air temperature on Mt. Emei is 24.90 °C at 1105 m; the adjusted air temperatures are 7.20 °C at 4301 m (the altitude of Location 1) and 6.41 °C at 4443 m (the altitude of Location 2), which are 4.85 and 4.41 °C lower than the temperatures at Location 1 (12.04 °C) and Location 2 (10.82 °C) in the interior plateau, respectively. Similarly, in June, the air temperature on Mt. Qingcheng is 20.63 °C at 1267 m; the adjusted temperatures are 0.79 °C at 4811 m (the altitude of Location 3) and 1.19 °C at 4740 m (the altitude of Location 4), which are 6.38 and 7.22 °C lower than the temperature over the interior plateau (Table 4). Moreover, the results demonstrate that the air temperature at given elevations gradually increases from the eastern edge to the interior plateau.

This analysis verifies that the main plateau is warmer than its surroundings and adjacent lowland areas and provides a general magnitude of the mass elevation effect of the plateau. Flohn (1953) first explained the mass elevation effect of the TP as a result of the altitudinal increase in solar radiation and the substantial longwave radiation at higher elevation; therefore, the TP is often called a heat source. Barry (2008) noted that sensible heat transferred from the surface and the latent heat of condensation due to precipitation from orographically induced cumulus cloud development contributes to the heating effect in the mountain atmosphere. Over the drier western part of the TP, the sensible heat flux is important; the total daily energy transfer from the plateau to the atmosphere reaches 220 W m⁻² in June (Yeh, 1982). East of 85°E, the latent and sensible heat fluxes are nearly identical (90 and 100 W m⁻², respectively). Moreover, over the southeastern plateau, convective activity provides a large heat input due to the latent heat of condensation (Yeh, 1982), which explains why the main plateau is a heat source and its air temperature is higher than over the surrounding and adjacent lowland areas.
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Figure 4. Air temperatures over the central/northern main plateau and the Qilian Mts. in (a) January and (b) July.

Figure 5. (a) Monthly temperature differences at an elevation of 4500 m and (b) temperature differences as a function of altitude between the central/northern main plateau and the Qilian Mts.

Table 3. Temperature and temperature differences ($\Delta T$) between Mt. Emei and two locations on the main plateau (units: °C).

| Longitude | Latitude | Elevation (m) | January | February | March | April | May | June | July | August | September | October | November | December |
|-----------|----------|---------------|---------|----------|-------|-------|-----|------|-----|--------|-----------|---------|----------|----------|
| $T_{\text{Mt. Emei}}$ | 103.29 | 29.36 | 1105 | 4.16 | 6.35 | 10.12 | 15.04 | 19.31 | 22.67 | 24.90 | 24.21 | 20.16 | 14.78 | 9.79 | 5.10 |
| $T_{\text{Location 1}}$ | 100.50 | 29.36 | 4443 | -3.35 | -1.87 | 0.94 | 3.38 | 6.15 | 9.30 | 10.82 | 10.65 | 8.07 | 4.46 | -0.92 | -3.56 |
| $T_{\text{Location 2}}$ | 90.00 | 29.36 | 4301 | -4.32 | -2.89 | 0.37 | 3.19 | 7.01 | 10.73 | 12.04 | 11.55 | 9.27 | 4.49 | -1.06 | -3.75 |
| $T_{\text{Emei adjusted}}$ | 4301 | -12.14 | -10.62 | -7.72 | -3.02 | 0.01 | 3.62 | 7.20 | 6.25 | 2.80 | -2.13 | -7.69 | -10.40 |
| $\Delta T_{\text{Emei adjusted}}$ | 4443 | -12.87 | -11.37 | -8.51 | -3.82 | -0.85 | 2.78 | 6.41 | 5.45 | 2.03 | -2.88 | -8.47 | -11.08 |
| $\Delta T_{\text{Location 1} - \text{Emei}}$ | 4443 | 9.52 | 9.51 | 9.44 | 7.20 | 7.00 | 6.52 | 4.41 | 5.20 | 6.04 | 7.34 | 7.55 | 7.52 |
| $\Delta T_{\text{Location 2} - \text{Emei}}$ | 4301 | 7.85 | 7.73 | 8.09 | 8.09 | 7.01 | 7.30 | 4.85 | 5.30 | 6.47 | 6.61 | 6.63 | 6.64 |

5.3. The spatiotemporal pattern of air temperatures over the main plateau

The above analysis demonstrates that the air temperatures at high altitudes over the main plateau are higher than in the free air over the surrounding areas due to the mass elevation effect of the plateau. To further deduce the spatiotemporal pattern of the mean temperatures over the main plateau, we sketch the distributions of the 10°C isotherm in the warm months (Figure 6). In May, it is at 3700–3800 m on the southern main plateau, at 3200–3300 m in the Hengduan Mts., at 4000–4100 m on the central main plateau and at 3300–3400 m on the northeast main plateau. In July, it reaches its highest locations, i.e. at 4600–4700 m on the southern main plateau, at 4300–4400 m in the Hengduan Mts., at 4800–4900 m on the central main plateau and at 4300–4400 m on the northeast main plateau. It is clear that the warmest month 10°C isotherm is higher on the central plateau than in the...
Table 4. Temperature and temperature differences ($\Delta T$) between Mt. Qingcheng and two locations on the main plateau.

|                | Longitude | Latitude | Elevation (m) | June (°C) |
|----------------|-----------|----------|---------------|-----------|
| $T_{\text{Qingcheng}}$ | 103.53    | 31.02    | 1267          | 20.63     |
| $T_{\text{Location 3}}$ | 100.00    | 31.02    | 4811          | 7.17      |
| $T_{\text{Location 4}}$ | 90.00     | 31.02    | 4740          | 8.41      |
| $T_{\text{adjusted Qingcheng}}$ |         |          |               | 4811      |
| $T_{\text{adjusted Qingcheng}}$ |         |          |               | 4740      |
| $\Delta T_{\text{Location 3 - Qingcheng}}$ |       |          |               | 6.38      |
| $\Delta T_{\text{Location 4 - Qingcheng}}$ |       |          |               | 7.22      |

other regions, confirming the existence of the mass elevation effect of the plateau.

5.4. The importance of the TP mass elevation effect for the highest treeline in the Northern Hemisphere

On both global and continental scales, previous work has suggested that temperature is the final factor for determining treeline altitude (Holtmeier and Broll, 2005) and that the warmest month 10°C isotherm and the warmth index of 15°C month are thought to coincide with Alpine treelines (Troll, 1973; Ohsawa, 1990). According to our analysis, the warmest month 10°C isotherm lies at 4600–4700 m on the southern main plateau and at 4300–4400 m in the Hengduan Mts. The warmth index at 4500 m asl for these two areas are 15.41 and 16.11 °C month, respectively (as calculated using Equation (3)). The warmth index at 4600–4700 m asl may reach 15°C month. These two areas also have sufficient annual precipitation (>500 mm) (Liao, 1990) for tree growth. Those temperature and precipitation conditions can explain why the highest treeline in the Northern Hemisphere occurs in the southeastern TP. Although the warmest month 10°C isotherm lies at 4800–4900 m on the central main plateau and 4300–4400 m on the northern main plateau, rainfall in these areas is insufficient (<400 mm) (Liao, 1990) for the growth of trees.

To further evaluate the implications of the mass elevation effect for Alpine treelines, we collected treeline data from the literatures (Figure 1). First, as stated above, air temperatures gradually increase from the easternmost to the interior main plateau, and the altitude of treelines follows a similar trend (Figure 1). The treelines along the eastern edge of the TP (on Qilian Mts. and in the transition region between the eastern TP and the Sichuan Basin) is typically below 3700 m. From the eastern edge to the inner TP, the treeline ascends to 4000 m east of the Maqin-Daofu-Jiulong line. Moreover, the treeline increases to 4600–4700 m westward in Zuogong and Lhasa; it even reaches 4900 m on some sunny slopes. Second, the air temperatures during the entire year in the interior main TP at 4500 m asl are approximately 3.58–6.63 °C higher than in the Sichuan Basin (Table 2). Similarly, the treelines in the interior TP are approximately 500–1000 m higher than in the eastern edge of the TP (Table 5). According to profiles 1 through 3 in Table 5, air temperatures at the treeline sites in the interior TP are primarily 9–11 °C, which are not lower than the air temperatures along the eastern/western edges of TP, even though treelines in the interior TP are approximately 500–1000 m higher than along the eastern/western edges. Therefore, the mass elevation effect raises the Alpine treeline in the interior TP because favourable temperatures for tree growth are present at higher altitudes on the TP.

6. Discussion

6.1. The differences between the mass elevation effect of the TP and the heat source in summer/heat sink in winter

The results presented herein demonstrate that the mass elevation effect of the TP occurs throughout the entire year,
Table 5. Treeline profiles along 29.7°, 30° and 31°N, and the July temperatures at the treeline sites.

| Profile | Treeline site | Longitude | Latitude | Treeline altitude (m) | Air temperature in July (°C) |
|---------|---------------|-----------|----------|-----------------------|-------------------------------|
| Profile 1 | Near 29.7°N | East of Nyemo River | 91.02 | 29.71 | 4750 | 10.19 |
|         |                | Porong Ka Monastery | 91.16 | 29.77 | 4600 | 9.54 |
|         |                | Milin-Linzhi | 94.27 | 29.84 | 4300 | 8.05 |
|         |                | Nyingchi | 94.77 | 29.58 | 4300 | 10.19 |
|         |                | Namjagbarwa Feng N | 95.19 | 29.63 | 4200 | 7.48 |
|         |                | Dongdala, Zuogong | 97.94 | 29.70 | 4300 | 10.77 |
|         |                | Shaluli Shan S | 99.74 | 29.75 | 4200 | 10.35 |
|         |                | Gongga Shan N | 102.10 | 29.76 | 3700 | 11.58 |
| Profile 2 | Near 30°N | Nanda Devi massif | 79.81 | 30.18 | 3700 | 10.20 |
|         |                | Dozam Khola | 82.04 | 30.07 | 4200 | 10.96 |
|         |                | SW of Damxung | 91.00 | 30.01 | 4280 | 11.36 |
|         |                | Kyi Chu catchment | 91.52 | 30.30 | 4850 | 10.42 |
|         |                | Reting Monastery | 91.55 | 30.30 | 4750 | 11.58 |
|         |                | Kyi Chu catchment | 92.13 | 30.10 | 4600 | 10.89 |
|         |                | NE of Batang | 99.56 | 30.10 | 4500 | 9.02 |
|         |                | Haizi Shan, Yidon, Sichuan | 99.57 | 30.29 | 4200 | 9.36 |
|         |                | Jiajin Shan-Daxiangling | 103.29 | 30.30 | 3700 | 9.06 |
| Profile 3 | Near 31°N | Yumnotri | 78.47 | 31.07 | 3750 | 7.72 |
|         |                | Gangotri Mountain | 78.77 | 31.00 | 4100 | 12.87 |
|         |                | Bhagirathi V. | 78.98 | 31.08 | 4250 | 12.02 |
|         |                | Damala, Changdu | 97.27 | 31.15 | 4700 | 13.71 |
|         |                | Chaudo Shan, Kangding Sichuan | 101.94 | 31.09 | 4000 | 11.76 |
|         |                | Siguniang Shan | 103.13 | 31.20 | 3800 | 13.55 |
|         |                | Guangguang Shan | 103.40 | 31.12 | 3400 | 17.27 |

even in cold months. Yeh (1979) and Gao (2005) also found that the TP supplied heat to the lower atmosphere during the entire year. However, it was suspected whether the effect exists in winter, because the TP is a heat sink in winter (Yeh and Chang, 1974; Yeh, 1979; Chen et al., 1985; Yeh and Wu, 1998; Gao, 2005). Although both the mass elevation effect and the heat source/sink arise from both sensible and latent heat fluxes (which is called the heating effect in the field of meteorology), these concepts are virtually different. The former corresponds to the elevated plateau surface which causes heating in the lower atmosphere via sensible and latent heat fluxes and subsequently lifts the mountain altitudinal belts. The latter corresponds to atmospheric heat exchange between the TP and adjacent areas. Owing to the release of sensible and latent heat throughout the entire year, the mass elevation effect occurs throughout the entire year. However, this conclusion does not mean that the TP acts as a heat source all year because air mass motions are important for heat exchange between the atmosphere of the TP and the surrounding areas. Previous studies have found that the prevailing westerlies split to the west of the plateau and converge on the eastern side in winter. However, a cyclonic circulation in the lower atmosphere that becomes anticyclonic at high levels characterizes the wind field in summer. In winter, most of the plateau are dominated by descending air except in the southeastern plateau, whereas ascending motion prevails in summer (Yeh et al., 1957). Therefore, the TP is a thermal source in summer and a thermal sink in winter except in the southeastern region of the plateau.

6.2. Why does the highest treeline in the Northern Hemisphere occur over the southeastern TP and not in other places on the TP?

Our results demonstrate that the warmest month 10°C isotherm is located at 4600–4700 m on the southern main plateau and at 4800–4900 m on the central main plateau. However, the highest treeline in the Northern Hemisphere does not occur in the central main plateau but on the southeastern plateau. This is because tree growth requires another condition, at least 500 mm of annual precipitation (Hou, 1982a, 1982b). In the central and northwestern plateau, the annual precipitation amounts to about 50–300 mm (Liao, 1990; Zheng and Li, 1990; Zhang et al., 2002; Wang et al., 2011) which is not sufficient for tree growth. Therefore, the highest treeline in the Northern Hemisphere occurs in the southeastern region of the TP.

6.3. Implication of the mass elevation effect for global treeline patterns

As De Quervain (1904) first proposed and used the concept of mass elevation effect to account for the observed tendency in temperature-related parameters, such as treeline and snowline, to occur at higher elevations in the Central Alps than in their outer margins, many studies have verified that mass elevation effect raises treelines by approximately 400 m higher in the Central Alps compared to the outer ranges (Tollner, 1949; Holtmeier, 2003; Barry, 2008). A similar phenomenon has been observed in other large massif mountains/plateaus, including the TP and South American Andes (Holtmeier, 2003; Han et al., 2012).
Moreover, the highest treelines in the Northern and Southern Hemispheres occur on the TP and in the Andes, respectively (Miehe et al., 2007; Hoch and Körner, 2005; Körner, 2012). Although the effect of the heat source on the general circulation and local climate in these two locations has been the focus of many studies for several decades (Flohn, 1953; Yeh, 1952; Yao and Erdogan, 1989; Vuille et al., 1999; Garreaud et al., 2009), the correlation between mass elevation effect and the treeline distribution has been neglected. Using the concept of mass elevation effect is very effective to explain extremely higher treelines and could greatly deepen our understanding of ecological patterns and mechanism of global treelines.

In addition to the 10°C isotherm in the warmest month and a warmth index of 15°C month that were used in this study, the coldness index (Ohsawa, 1990) and many other seasonal climatic factors, such as the growing season mean temperature of 6.7 ± 0.8°C (Körner, 1998; Körner and Paulsen, 2004) and the shortest growing season length of 100 days (Ellenberg, 1963), were also found to be closely related to treeline locations in some areas. However, the relationship between these factors and the treeline distribution has been shown to exhibit large differences at different locations. Therefore, selecting several climate factors would be better for a comparative study on global treelines in the future.

6.4. Temperature lapse rate on the TP

When studying mountain climates, the temperature lapse rate is typically a necessary parameter (Rolland, 2003). In this study, the lapse rates measured on Mt. Emei and Mt. Qingcheng were used for temperature adjustment calculations in the Sichuan Basin according to the reported references (Table 1). However, the lapse rate varies from approximately 0.98°C 100 m−1 in dry air (the dry-air adiabatic lapse rate) to approximately 0.48°C 100 m−1 in moist air (the saturated adiabatic lapse rate (Dodson and Marks, 1997). The dry adiabatic lapse rate is different than the wet lapse rate; the lapse rate also changes with locations. More precise lapse rates for temperature adjustment must be acquired in the future. Similarly, the humidity varies both spatially and seasonally on the TP (Liao, 1990; Zhang et al., 2002). Therefore, the lapse rate exhibits large spatial and temporal variability on the plateau. Moreover, lapse rates on the TP may be smaller than the global average temperature lapse rate due to the mass elevation effect of the TP because temperature lapse rates are steeper on isolated mountains near the sea than within extensive mountain ranges that provide their own heating (Hastenrath, 1968; Flenery, 1995). The mean annual lapse rate in the European Alps ranges from 5.4 to 5.8°C km−1. Previous work revealed a clear and consistent seasonal variation with higher lapse rates from April to September for the minimum, mean and maximum temperatures (Rolland, 2003). However, there are few reports regarding the seasonal variation in lapse rates for the TP. It has also been noted that lapse rates exhibit considerable variability in relation to the climatic zone, season (Hastenrath, 1968), air mass type (Yoshino, 1966) and local topography (Flenery, 2007; Barry, 2008). Monthly mean lapse rates on the TP and their spatiotemporal variation deserve a closer examination in the future.

7. Conclusions

Owing to mass elevation effect, air temperatures gradually increase from the eastern edge to the interior main TP. The monthly mean air temperature in the interior main plateau is approximately 2–7°C higher than in the surrounding mountains and adjacent lowland areas at given altitudes of 4000–6000 m. At elevation of 4500 m (the average elevation of the plateau), monthly air temperature difference is from 3.58°C (April) to 6.63°C (June) and 1.6°C (July) to 7.7°C (March) relative to the Sichuan Basin and Qilian Mts., respectively. This causes that the treelines are 500–1000 m higher in the interior TP than in the eastern border areas. Therefore, mass elevation effect contributes greatly to the occurrence of the highest treeline (4700–4900 m) of the Northern Hemisphere, which is present on the southeastern TP.

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Appendix

Table A1. List of 166 treeline sites in the Tibetan Plateau used in this study.

| Site name                | Longitude (°) | Latitude (°) | Elevation (m) | References                        |
|--------------------------|---------------|--------------|---------------|-----------------------------------|
| Baima Xueshan E          | 99.1          | 28.4         | 4100          | Investigating group for South-to-North Water Transfer Project (1978) |
| Baxoi county             | 96.7          | 29.8         | 4900          | Miehe et al. (2007)               |
| Biluo Xueshan            | 98.9          | 27.5         | 3530          | Investigating group for South-to-North Water Transfer Project (1978) |
| Chola Shan (Sichuan)     | 99.1          | 32.0         | 4200          | Jiang et al. (2004)               |
| Dabanzhao                | 103.0         | 31.7         | 3750          | Hu and Song, 1961; pers. comm.    |
| Dafeng Ding, Meigu County, Sichuan | 103.3 | 28.6 | 3500    | Zheng (1997)                     |

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| Site name | Longitude (°) | Latitude (°) | Elevation (m) | References |
|----------|--------------|--------------|---------------|------------|
| Duglama Shan, Qamdo | 97.3 | 31.2 | 4600 | Zhang et al. (1988) |
| Dajin Chuan and Xiaojin Chuan | 102.0 | 31.5 | 3900 | Zheng (1997) |
| Duming-Zhongdian (N) | 99.7 | 26.6 | 4130 | Investigating group for South-to-North Water Transfer Project (1978) |
| Duming-Zhongdian (S) | 99.7 | 26.6 | 4150 | Investigating group for South-to-North Water Transfer Project (1978) |
| Gaershi Shan N, Yajiang County, sichuan | 100.9 | 30.0 | 4000 | Hou (1982a, 1982b) |
| Gaoligong Shan | 98.8 | 27.0 | 3800 | Hou (1963) |
| Gaoligongshan pianma pass | 98.5 | 28.0 | 3500 | Investigating group for South-to-North Water Transfer Project (1978) |
| Gongga Shan E | 102.1 | 29.6 | 3500 | Zhong and Zheng (1983) |
| Gongga Shan N | 102.1 | 29.8 | 3700 | Zhong and Zheng (1983) |
| Gongga Shan S | 102.1 | 29.6 | 3800 | Zhong and Zheng (1983) |
| Gongga Shan W | 102.1 | 29.6 | 4000 | Zhong and Zheng (1983) |
| Gong-jun-dah | 98.5 | 31.0 | 3900 | Zhang et al. (1988) |
| Haizi Shan, Yidun, sichuan | 99.5 | 30.3 | 4200 | Jiang et al. (2004) |
| Jinyang County, Xinjiang | 103.3 | 27.9 | 3700 | Zheng (1997) |
| Kanggar, Daocheng County, Sichuan | 100.2 | 28.6 | 4300 | Jiang et al. (2004) |
| Kya’gyu Shan SE | 102.5 | 30.3 | 3700 | Han (2011) |
| Lancang Jiang N, Chuka | 98.1 | 30.0 | 4250 | Hou (1982a, 1982b) |
| Lancang Jiang S, Chuka | 98.1 | 30.0 | 4400 | Hou (1982a, 1982b) |
| Lancang River, Ngom Chu (Shangka) | 96.8 | 31.4 | 4400 | Liu and Lu (1990) |
| Lancang River, Qamdo | 97.1 | 31.5 | 4300 | Liu and Lu (1990) |
| Lancang River, Za Qu (Wongdagang) | 97.2 | 31.6 | 4400 | Liu and Lu (1990) |
| Lhong-ong-Dengqen | 95.7 | 30.9 | 4300 | Zhang et al. (1988) |
| Mainkung-Dongba | 98.3 | 28.4 | 4150 | Zhang et al. (1988) |
| Medog County, Tibet | 95.2 | 29.6 | 4000 | Zhang et al. (1988) |
| Moirigkawagarbo E I | 98.7 | 28.2 | 4450 | Investigating group for South-to-North Water Transfer Project (1978) |
| Moirigkawagarbo E II | 98.6 | 28.5 | 3700 | Schickhoff (2005) |
| Moirigkawagarbo W | 98.7 | 28.5 | 4220 | Investigating group for South-to-North Water Transfer Project (1978) |
| Namjagbarwa Feng N | 95.2 | 29.6 | 4200 | Li (1984) |
| Namjagbarwa Feng S | 95.1 | 29.5 | 3900 | Peng et al. (1997), Zheng (1997) |
| Ningjing Shan | 99.0 | 29.8 | 4200 | Zhang et al. (1988) |
| North of Lepa | 97.1 | 29.0 | 3900 | Schickhoff (2005) |
| NW of Litang | 100.0 | 30.5 | 4650 | Schickhoff (2005) |
| Nyingser La | 98.8 | 27.9 | 4250 | Schickhoff (2005) |
| Parlung Zangbo catchment | 96.8 | 29.5 | 3900 | Schickhoff (2005) |
| Parlung Zangbo V, Bomi | 95.7 | 29.8 | 4100 | Jiang et al. (2004) |
| Qamdo-Zha’g’yab | 97.4 | 30.8 | 4300 | Zhang et al. (1988) |
| Sang Qu | 97.4 | 29.2 | 4150 | Schickhoff (2005) |
| SE of Zoggen | 99.1 | 31.8 | 4350 | Schickhoff (2005) |
| Shaluli Shan S | 99.7 | 29.8 | 4200 | Liu (1981) |
| Siguniang Shan | 103.1 | 31.2 | 3800 | Liu (1981) |
| South section of Taiyangshan E, sichuan | 101.3 | 28.2 | 3600 | Zheng and Gao (1984) |
| South section of Taiyangshan W, sichuan | 101.0 | 27.9 | 3900 | Zheng and Gao (1984) |
| Xuebaoding | 103.7 | 32.7 | 3800 | Zhang et al. (2006) |
| Yading Nature Reserve | 100.5 | 28.5 | 4440 | Shi et al. (2008) |
| Yanjing-Chuka | 98.7 | 29.1 | 4250 | Zhang et al. (1988) |
| Yulong Xueshan | 100.1 | 27.4 | 3900 | Li et al. (1983) |
| Yunling-Deqen N | 98.9 | 28.5 | 4050 | Li et al. (1983) |
| Yunling-Deqen S | 98.9 | 28.5 | 4200 | Li et al. (1983) |
| Zayü | 96.4 | 29.5 | 4050 | Schickhoff (2005) |
| Zayü County | 97.5 | 28.6 | 4200 | Zhang et al. (1988) |
| Zayü Qu (east branch) | 97.5 | 28.6 | 4000 | Zheng (1997) |
| Zhe Gu Shan, sichuan | 102.7 | 31.9 | 3750 | Körner and Paulsen (2004) |
| Zheduo Shan (Kangding, sichuan) | 101.9 | 31.1 | 4000 | Liu and Qu (1980) |
| Zoggen | 98.8 | 32.1 | 4700 | Schickhoff (2005) |
Table A1. Continued.

| Site name                                 | Longitude (°) | Latitude (°) | Elevation (m) | References          |
|-------------------------------------------|---------------|--------------|---------------|---------------------|
| Barbung Khola                             | 83.3          | 28.8         | 4400          | Schickhoff (2005)   |
| Barun Khola N                             | 87.1          | 27.8         | 4500          | Schickhoff (2005)   |
| Beas River                                | 77.4          | 32.0         | 3550          | Schickhoff (2005)   |
| Bhagirathi V.                             | 79.0          | 31.1         | 4250          | Schickhoff (2005)   |
| Biafo Glacier                             | 75.8          | 35.6         | 4100          | Schickhoff (2005)   |
| Black Mountains N                         | 90.7          | 27.4         | 4250          | Schickhoff (2005)   |
| Boqu Valley N, Qomolangma                 | 86.0          | 28.1         | 3900          | Zheng et al. (1975) |
| Boqu Valley S, Qomolangma                 | 86.1          | 28.0         | 3800          | Zheng et al. (1975) |
| Burzil                                    | 75.0          | 34.9         | 3550          | Schickhoff (2005)   |
| Cha Lungpa V.                             | 83.6          | 28.9         | 4150          | Schickhoff (2005)   |
| Chamba                                    | 77.0          | 32.6         | 4200          | Schickhoff (2005)   |
| Chentang, Tibet                           | 87.4          | 27.8         | 4000          | Jiang et al. (2004) |
| Chilime V.                                | 85.2          | 28.4         | 4500          | Schickhoff (2005)   |
| Chulungche                                | 86.8          | 27.9         | 4400          | Schickhoff (2005)   |
| Chumbi V.                                 | 89.0          | 27.7         | 3800          | Schickhoff (2005)   |
| Chyochyo Danda S                          | 85.7          | 28.0         | 3700          | Schickhoff (2005)   |
| Cona County, Tibet                        | 92.3          | 27.6         | 4000          | Li (1984)            |
| Dachchigam woodland                       | 75.0          | 34.2         | 3550          | Schickhoff (2005)   |
| Dagan V.                                  | 75.0          | 34.3         | 3550          | Schickhoff (2005)   |
| Dhaola Dhar Range                         | 76.9          | 32.3         | 3550          | Schickhoff (2005)   |
| Diamir                                    | 74.4          | 35.0         | 4150          | Schickhoff (2005)   |
| Dozam Khola N                             | 82.0          | 30.1         | 4150          | Schickhoff (2005)   |
| Dozam Khola S                             | 82.0          | 30.0         | 4200          | Schickhoff (2005)   |
| Dupku N                                   | 85.6          | 28.1         | 4020          | Schickhoff (2005)   |
| Dupku S                                   | 85.6          | 28.1         | 4200          | Schickhoff (2005)   |
| Flowers National Park                     | 79.6          | 30.7         | 3750          | Schickhoff (2005)   |
| Gannazangbu Valley, Qomolangma            | 87.7          | 27.7         | 3800          | Zheng et al. (1975) |
| Ghasa                                     | 83.6          | 28.6         | 4050          | Schickhoff (2005)   |
| Gyalap Peri                               | 94.9          | 29.9         | 3900          | Schickhoff (2005)   |
| Gyirong V., Tibet                         | 85.3          | 28.4         | 4000          | Jiang et al. (2004) |
| Hispar V                                  | 75.1          | 36.2         | 4350          | Schickhoff (2005)   |
| Hushe V.                                  | 76.4          | 35.5         | 4050          | Schickhoff (2005)   |
| Jargeng Khola                             | 83.9          | 28.7         | 4200          | Schickhoff (2005)   |
| Jelep La W                                | 88.9          | 27.3         | 4000          | Schickhoff (2005)   |
| Kaghan                                    | 73.6          | 34.9         | 3775          | Schickhoff (2005)   |
| Kalong Chu                                | 91.0          | 27.9         | 3900          | Schickhoff (2005)   |
| Kamri Pass                                | 74.9          | 34.7         | 3650          | Schickhoff (2005)   |
| Kone Khola                                | 84.0          | 28.7         | 4300          | Schickhoff (2005)   |
| Kulu V.                                   | 77.1          | 32.2         | 3700          | Schickhoff (2005)   |
| Kyi Chu catchment                         | 91.6          | 30.3         | 4850          | Miehe et al. (2007) |
| Ladakh                                    | 77.7          | 34.4         | 4250          | Schickhoff (2005)   |
| Lhonak V.                                 | 88.3          | 27.8         | 4500          | Schickhoff (2005)   |
| Liddar V.                                 | 75.3          | 34.2         | 3550          | Schickhoff (2005)   |
| Lupghar V. and upper Chupursan V.         | 74.7          | 36.7         | 3950          | Schickhoff (2005)   |
| Maimling County, Tibet                   | 94.2          | 29.2         | 4000          | Jiang et al. (2004) |
| Mainling N                                | 93.9          | 29.1         | 4300          | Schickhoff (2005)   |
| Marol                                     | 76.2          | 34.8         | 3900          | Schickhoff (2005)   |
| Marpha                                    | 83.7          | 28.8         | 4050          | Schickhoff (2005)   |
| Morkhun V.                                | 74.9          | 36.6         | 3950          | Schickhoff (2005)   |
| Mugu Karnali V                            | 82.7          | 29.7         | 4050          | Schickhoff (2005)   |
| Muktiniath                                | 83.8          | 28.9         | 4150          | Schickhoff (2005)   |
| Nanda Devi massif                         | 79.8          | 30.2         | 3700          | Schickhoff (2005)   |
| Narimthang                                | 91.2          | 27.9         | 3900          | Schickhoff (2005)   |
| Nilgiri                                   | 83.7          | 28.7         | 4400          | Schickhoff (2005)   |
| Nyalam                                    | 86.0          | 28.2         | 4050          | Fang (1995)         |
| Nyemo River E                             | 90.0          | 29.3         | 4800          | Schickhoff (2005)   |
| Nyengchi S                                | 94.2          | 29.3         | 4500          | Shi et al. (2008)   |
| Orka La                                   | 92.0          | 27.4         | 3950          | Schickhoff (2005)   |
| Pamtschü                                  | 92.0          | 29.3         | 4600          | Schickhoff (2005)   |
| Pangoche N                                | 86.8          | 27.9         | 4250          | Schickhoff (2005)   |
| Porong Ka Monastery                       | 91.2          | 29.8         | 4600          | Schickhoff (2005)   |
| Rongxarq Valley N, Qomolangma             | 86.4          | 28.1         | 4100          | Zheng et al. (1975) |
| Rupal V.                                  | 74.7          | 35.2         | 4150          | Schickhoff (2005)   |
| Sankosh Valley                            | 90.1          | 27.7         | 4200          | Schickhoff (2005)   |
Table A1. Continued.

| Site name                  | Longitude (°) | Latitude (°) | Elevation (m) | References                      |
|----------------------------|---------------|--------------|---------------|---------------------------------|
| Sarat                      | 74.8          | 36.4         | 4100          | Schickhoff (2005)               |
| Satpara/Deosai             | 75.6          | 35.1         | 4200          | Schickhoff (2005)               |
| Se La                      | 92.1          | 27.6         | 3950          | Schickhoff (2005)               |
| Shey Gompa                 | 82.9          | 29.3         | 4200          | Schickhoff (2005)               |
| Shingo La                  | 76.9          | 32.9         | 3900          | Schickhoff (2005)               |
| Singalila National Park    | 88.1          | 27.4         | 3650          | Schickhoff (2005)               |
| Solu Khola                 | 86.5          | 27.6         | 4000          | Schickhoff (2005)               |
| Sygera Mts., Nyingchi      | 94.2          | 30.0         | 4300          | Jiang et al. (2004)             |
| Tanggu                     | 88.5          | 27.9         | 4100          | Schickhoff (2005)               |
| Tikeapsa                   | 85.6          | 28.2         | 4540          | Schickhoff (2005)               |
| Tons V.                    | 78.3          | 31.2         | 4050          | Schickhoff (2005)               |
| Tremo La                   | 89.3          | 27.7         | 4000          | Schickhoff (2005)               |
| Trisuli catchment          | 85.2          | 28.6         | 4300          | Schickhoff (2005)               |
| Tsamtshu                   | 90.5          | 29.0         | 4650          | Schickhoff (2005)               |
| Tungnath                   | 79.3          | 30.5         | 3600          | Schickhoff (2005)               |
| upper Bhutna V.            | 76.3          | 33.5         | 3800          | Schickhoff (2005)               |
| Wardwan/Chenab V.          | 75.8          | 33.8         | 3550          | Schickhoff (2005)               |
| Xiabaxia-Kuer              | 92.4          | 27.6         | 4100          | Zhang et al. (1988)             |
| Yadong County, Tibet       | 88.9          | 27.5         | 4000          | Zhang et al. (1988)             |
| Yangri Danda               | 85.7          | 28.0         | 3700          | Schickhoff (2005)               |
| Yumnotri                   | 78.5          | 31.1         | 3750          | Schickhoff (2005)               |
| Zemu V.                    | 88.2          | 27.5         | 4100          | Schickhoff (2005)               |
| Zoji La                    | 75.4          | 35.3         | 3550          | Schickhoff (2005)               |
| Kongur-Oytagh              | 74.4          | 39.0         | 3500          | Schickhoff (2005)               |
| Wuytak                     | 75.3          | 38.9         | 3400          | Schickhoff (2005)               |
| Baihui Jiang National Natural Reserve | 104.4 | 32.8         | 3450          | Sun and Feng (1998)             |
| Hexi mountain-oasis-desert area | 100.7 | 38.4         | 3200          | Wang et al. (2001)              |
| Hutou Shan N               | 103.3         | 34.2         | 3800          | Feng and Sun (1990)             |
| Laji Shan                  | 101.6         | 36.0         | 3350          | Fang (1995)                     |
| Lenglong Ling N            | 102.2         | 37.7         | 3250          | Chen et al. (1994)              |
| Lianhuashan Nature Reserve, Gansu | 103.8 | 34.9         | 3400          | Li and Zhang (2000)             |
| Niuxin Shan N              | 100.3         | 38.1         | 3450          | Chen et al. (1994)              |
| Qilian mountains N         | 102.0         | 37.4         | 3330          | Wang et al. (2001)              |
| Qilian mountains NE        | 102.6         | 37.0         | 3200          | Jiang et al. (2004)             |
| Qingshiling N              | 102.2         | 37.1         | 3200          | Chen et al. (1994)              |
| Qingshiling S              | 102.2         | 37.1         | 3500          | Chen et al. (1994)              |
| Suyiyahei Mountain        | 103.9         | 33.8         | 3700          | Feng and Sun (1990)             |
| Xinglong Shan              | 104.0         | 35.8         | 2750          | Liu (1981)                      |
| Xiqing Shan, Qinghai       | 101.7         | 34.7         | 3800          | Jiang et al. (2004)             |
| Yeniuh Shan N              | 100.4         | 38.2         | 3150          | Chen et al. (1994)              |
| Zhangye Nanshan            | 98.6          | 39.4         | 3200          | Zhang (1997)                    |

Supporting Information

The following supporting information is available as part of the online article:

Table S1. Temperatures at elevations 4000–6000 m in the Hengduan Mts. (unit: °C).

Table S2. Temperatures at elevations 4000–6000 m in the southern main plateau (unit: °C).

Table S3. Temperatures at altitudes 4000–6000 m in the central main plateau (unit: °C).

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