

The implication of mass elevation effect of the Tibetan Plateau for altitudinal belts

YAO Yonghui¹, XU Mei², *ZHANG Baiping^{1,3}

1. State Key Laboratory of Resource and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China; 2. China Institute of Water Resources and Hydropower Research, Beijing 100044, China; 3. Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China

Abstract: The heating effect (or mass elevation effect, MEE) of the Tibetan Plateau (TP) is intense due to its massive body. Some studies have been undertaken on its role as the heat source in summer and its implications for Asian climate, but little has been known of the implications of its MEE for the distribution of mountain altitudinal belts (MABs). Using air temperature data observed and remotely sensed data, MAB/treeline data, and ASTER GDEM data, this paper compares the height of MABs and alpine treelines in the main TP and the surrounding mountains/lowland and explains the difference from the point of view of MEE. The results demonstrate: 1) at same elevation, air temperature and the length of growing season gradually increase from the eastern edge to the interior TP, e.g., at 4500 m (corresponding to the mean altitude of the TP), the monthly mean temperature is 3.58°C higher (April) to 6.63°C higher (June) in the interior plateau than in the Sichuan Basin; the 10°C isotherm for the warmest month goes upward from the edge to the interior of the plateau, at 4000 m in the Qilian Mts. and the eastern edges of the plateau, and up to 4600–5000 m in Lhasa and Zuogong; the warmth index at an altitude of 4500 m can be up to 15°C·month in the interior TP, but much lower at the eastern edges. 2) MABs and treeline follow a similar trend of rising inwards: dark-coniferous forest is 1000–1500 m higher and alpine steppe is about 700–900 m higher in the interior TP than at the eastern edges.

Keywords: Tibetan Plateau; mass elevation effect; mountain altitudinal belt; treeline; the warmth index; the 10°C isotherm in the warmest month

J. Geogr. Sci. 2015, 25(12): 1411–1422

DOI: 10.1007/s11442-015-1242-3

1 Introduction

More than one hundred years ago, De Quervain (1904) proposed the concept of Massenerhebungseffekt (Mass elevation effect, briefly MEE) to account 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. This phenomenon has also been discovered and reported in other places around the world (Leuschner, 1996; Holtmeier, 2003; Flenley, 2007; Barry, 2008). Due to MEE, growing season is relatively longer and warmer at any given elevation in the central mountain ranges. These favorable conditions make treeline rise for about 400 m higher in the central Alps compared to the outer ranges (Holtmeier,

Received: 2015-04-30 **Accepted:** 2015-05-27

Foundation: National Natural Science Foundation of China, No.41571099; No.41001278

Author: Yao Yonghui (1975–), PhD, specialized in GIS/RS application and mountain environment. E-mail: yaoyh@lreis.ac.cn

***Corresponding author:** Zhang Baiping (1963–), Professor, E-mail: zhangbp@lreis.ac.cn

2003). Grubb (1971) also stated that the upper limit of lowland rain forest is at about 700–900 m and that of lower montane rain forest at about 1200–1600 m on small, isolated mountains and outlying ridges of major ranges, whereas approximately 1200–1500 m and 1800–2300 m, respectively, on the main ridges of major ranges. Similar phenomena were observed on the TP, Andes and other large mountains and plateaus. In the southeastern TP, alpine treelines climb up to approximately 4600–4700 m (Troll 1973; Zheng and Li, 1990) and even higher (4900 m) on a few sunny slopes (Miehe *et al.*, 2007), which represent the highest treeline in the Northern Hemisphere. The highest snowline in the Northern Hemisphere also distributes on the TP, at about 6000 m, but in the southwestern TP (Shi *et al.*, 1992; Han *et al.*, 2011).

The heating effect of the TP was identified as early as the 1950s. Flohn (1957) and Ye (1957) separately found that the TP was a summertime atmospheric heat source. Since then, it has been related to Eurasian weather and climate and even to the atmospheric general circulation (Ye, 1982; Ye and Wu, 1998; Yanai and Wu, 2006; Ye and Chang, 1974; Chen *et al.*, 1985; Wu *et al.*, 1997; Zhao *et al.*, 2013). Flohn (1953) first proposed that elevated plateau surfaces, such as those of Tibet and the Altiplano in South America, are warmer in summer than the adjacent free air as a result of the altitudinal increase in solar radiation and the substantial longwave radiation at higher elevation. 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. Ye (1982) calculated the sensible heat and the latent heat of the TP. Over the drier western part of the TP, the sensible heat flux is significant and the total daily sensible energy transfer from the plateau surface to the atmosphere reaches 220 Wm^{-2} in June. East of longitude 85°E , the latent and sensible heat fluxes are nearly identical (90 and 100 Wm^{-2} , respectively). The maximum heating rates in June for the layer between 600 and 150 mb amount to $+1.8^\circ\text{C day}^{-1}$ from sensible heat, $+1.4^\circ\text{C day}^{-1}$ from latent heat, and radiative cooling of $-1.5^\circ\text{C day}^{-1}$, giving a net heating of $+1.7^\circ\text{C day}^{-1}$. Various estimates suggest that the heating is about 2°C day^{-1} over the eastern half of the Plateau (Chen *et al.*, 1985). Moreover, due to the heating effect of the TP, it is an important negative vorticity source of the summer atmospheric movement (Wu *et al.*, 2005).

Such substantial heating must have large effects not only on the climate of the TP but also the ecological patterns of the plateau, especially the spatial pattern of mountain altitude belts (Zheng and Li, 1990; Liu *et al.*, 2003). Yao and Zhang (2013a, 2013b, 2013c, 2014) studied quantitatively the mass elevation effect of the plateau by comparing monthly mean air temperature differences at given 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, and discussed the implications of mass elevation effect for treelines by considering the 10°C isotherm for the warmest month and warm index of $15^\circ\text{C}\cdot\text{months}$. However, the implication of mass elevation effect for the whole ecological pattern of the plateau has been rarely involved. This paper intends to explore the implication of mass elevation effect for altitudinal belts with observed and estimated air temperature data, DEM and altitudinal belt data.

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 km², mostly 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 Gangdisé and Tanggula Mountains lie in the interior TP and divide the main plateau into three parts (i.e. the southern, central and northern main plateau). The Qaidam Basin, located in the northeast of the TP, is approximately only 3000 m asl and separates the Qilian Mts. from the main plateau.

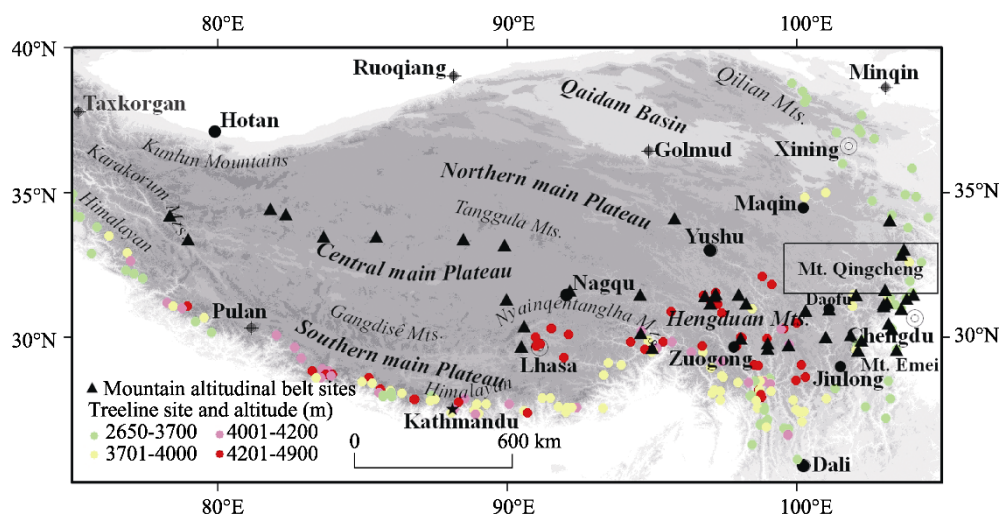


Figure 1 Sketch map of the Tibetan Plateau and treeline and mountain altitudinal belt sites

3 Data and data sources

3.1 Air temperature data

Two kinds of air temperature data are used in this paper. Observed air temperature data were downloaded from the China Meteorological Information Center (<http://cdc.cma.gov.cn/index.jsp>). MODIS land surface temperature (LST) data were processed with meteorological data for 2001–2007 from 137 stations and the ASTER GDEM data (Yao and Zhang, 2013). The MODIS LST data were the Terra Monthly Land Surface Temperature/Emissivity (MOD11C3) product at 0.05° geographic Climate Modeling Grid (CMG) spatial resolution, downloaded from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/lpdaac/products/modis_products_table). Geographical weighted regression (GWR) methods were used to estimate air temperature, and the root mean square error (RMSE) for each month ranges from 1.13°C for August to 1.53°C for March. These data such estimated are spatially continuous and contain more detailed air temperature information than the observed but rather scattered data.

3.2 Mountain altitudinal belt (MAB) and treeline data

Zhang *et al.* (2008, 2009) collected 544 spectra of mountain altitudinal belts, 594 sites for treeline data, and 148 sites for snowline data from the published literature for the global and

integrated them into a digital mountain altitudinal belt information system. Of them, a total of 267 treeline and 39 MAB data are used in this paper.

4 Methods

Montane dark coniferous forest, alpine shrub meadow, alpine meadow, and treelines are taken into account along three profiles (the Mt. Erlang-Nyainqentanglha profile: along Mt. Erlang-Mt. Gaoshi-Nyainqentanglha Mts.; the Mt. Guangguang-Tuoba Beishan profile: along Mt. Guangguan-Mt. Siguliang-Tuoba Beishan, and the Mt. Wutai-Amugang profile: along Mt. Wutai-Tanggula Mts. -Amugang), to study the distribution principles of the limits of MABs, and to calculate the mass elevation effect as temperature difference at the same elevation between the interior TP and the outer edges. Lastly, the mean temperature and the 10°C isotherm for the warmest month and the warm index of 15°C·months are used to study the implications of mass elevation effect for the MABs.

Firstly, according to the estimated air temperature data and ASTER GDEM, air temperatures and altitudes at the sites of MABs are extracted. Secondly, for the east edges or the neighboring areas, the extracted air temperatures were adjusted to the higher altitudes by Equation (1):

$$T_{\text{adjusted}} = T + (h - H) \times \partial \quad (1)$$

where ∂ is the lapse rate, T is the air temperature at a height h and T_{adjusted} is the adjusted air temperature at an elevation H . There are several lapse rate data available in the western Sichuan Basin, between 0.42 and 0.60°C/100 m⁻¹ (Liu, 1992; Wu, 1996; Zheng *et al.*, 1986; Xie 2006), and the lapse rates measured in Mt. Emei (0.55°C/100 m⁻¹ for July and 0.51°C/100 m⁻¹ for January) is relatively creditable, for Mt. Emei is located at the southwestern edge of the Sichuan Basin and at the easternmost edge of the Hengduan Mountains Therefore, the lapse rates of Mt. Emei were selected for the air temperature adjustment calculations in this paper (Table 1).

We then projected the elevation at which occurs the 10°C isotherm for the warmest month mean temperature and the warmth index (WI) at 4500 m (which corresponds to the mean elevation of the main plateau) based on the estimated monthly mean air temperatures and the ASTER GDEM data. The 10°C isotherms were extracted from the estimated air temperature data, and the corresponding altitudes were obtained from the ASTER GDEM data using ArcGIS. WI at the mean elevation of the main plateau (4500 m asl) is calculated as follows:

$$WI = \sum (t - 5) \quad (2)$$

where 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). Previous studies have shown that the warmest month 10°C isotherm and 15°C·month warmth index exhibit the best overall occurrence of forest upper limits (Troll, 1973; Ohsawa, 1990). These climatic indexes could be used to explore the potential altitude of treelines and the correlation between mass elevation effect and the MABs/treeline position.

5 Results

5.1 MABs and treelines rise gradually from the easternmost to the interior plateau

(1) Montane dark coniferous forest

Along the Mt. Erlang-Nyainqentanglha profile, montane dark coniferous forest rises westwards: at about 2200–2900 m in the westernmost Sichuan Province (such as Mt. Emei and Mt. Erlang), at about 3000–4000 m at the eastern edges of the Plateau (such as Mt. Gongga, Mt. Zheduo and Mt. Gaoshi), up to 3000–4300 m in the Hengduan Mts. (such as Mt. Shaluli and Mt. Ningjing), and even up to 3200–4500 m in the interior TP (Figure 2a). The same trend is observed along the Mt. Guangguang-Tuoba Beishan profile: about 2400–3700 m of the eastern edges of the Plateau (such as Beichuan, Mt. Guangguang, and Mt. Siguliang), and about 3200–4400 m westward to the interior TP (such as Changdu) (Figure 2b).

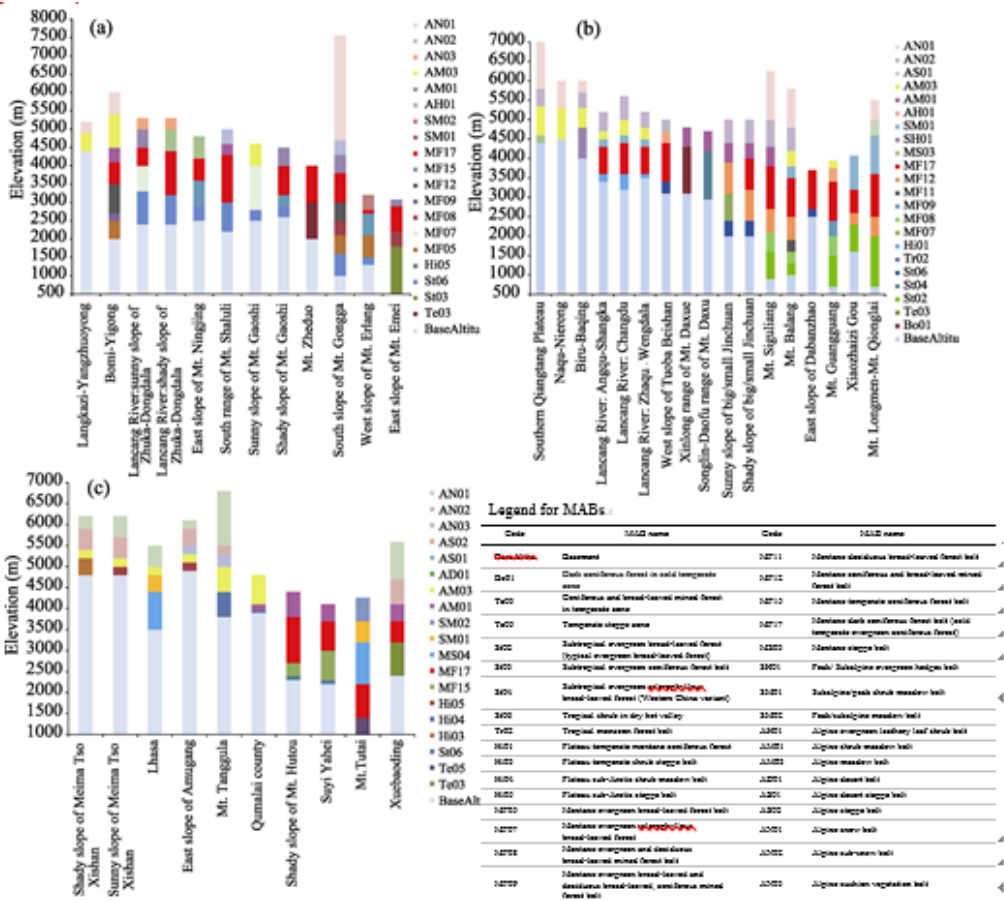


Figure 2 Mountain altitudinal belts along three profiles (a. the Mt. Erlang-Nyainqentanglha profile; b. the Mt. Guangguang-Tuoba Beishan profile; c. the Mt. Wutai-Amugang profile)

(2) Alpine shrub meadow and alpine meadow belts

Alpine meadow is at about 3700–4500 m in the eastern edges of the Plateau and rises to about 4400–5400 m in the interior TP. For example, along the Mt. Erlang-Nyainqentanglha profile, it is at 4000–4500 m at the eastern edges of the plateau (such as at Mt. Gaoshi) and about 4400–5400 m in the interior TP (such as at Bomi and Nyainqentanglha Mts.) (Figure 2a). Along the Mt. Guangguang-Tuoba Beishan profile, it is at about 3700–4200 m at the

eastern edge of the plateau (such as at Mt. Guangguang and Mt. Siguliang) and 4500–5400 m in the interior TP (westward to Changdu) (Figure 2b). Along the Mt. Wutai-Amugang profile, it is at 3700–4400 m at the eastern edges of the Plateau, 4100–4800 m westward to the Qumalai county, 4400–5000 m in the Tangula Mts., and 5000–5400 m westward further to the interior TP (such as at Amugang) (Figure 2c).

(3) Treelines

Treelines also rise from the easternmost to the interior TP. Treelines are typically below 3700 m along the eastern edge of the TP. For example, 3200 m in the Qilian Mts., about 3250 m on Mt. Erlang, 3700 m on Minshan and Mt. Gongga. They ascend to about 4000 m east of the Maqin-Daofu-Jiulong line, and to 4600–4700 m westward in Zuogong and Lhasa, even up to 4900 m on some sunny slopes (Figure 1). Normally, treelines are about 1000–1500 m higher in the interior Plateau than in the eastern edges and adjacent lowlands.

In short, MABs and treelines all gradually ascend from the easternmost to the interior TP. This is the so-called “mass elevation effect (MEE)” (De Quervain, 1904; Grubb, 1971; Holtmeier, 2003), namely, growing season is longer and warmer at any given elevation in the interior mountains than in the outer mountain ranges. This makes treelines rise by about 400 m in the central Alps compared to the outer ranges (Barry, 2008; Holtmeier, 2003). As for the TP, MEE is much stronger due to its supsize body.

5.2 Mass elevation effect of the TP

(1) Gradual increase of air temperatures at the same elevation from the easternmost to the interior plateau

The air temperatures at the MABs sites on the eastern edges are adjusted to the altitudes of the sites on the interior TP by Equation (1) (shown in Table 2). Along the Mt. Erlang-Nyainqentanglha profile, monthly mean temperature is below -12°C for January and 2°C for July at 5292 m on the east of Mt. Gaoshi, and it is above -11°C and 4°C , respectively, at the same elevation in the interior TP. The same trend can be seen along the Mt. Guangguang-Tuoba Beishan profile and along the Mt. Wutai-Amugang profile (Table 2). That is to say, air temperatures at same elevations increase gradually from the easternmost to the interior plateau.

(2) Mass elevation effect of the Tibetan Plateau

Differences in monthly air temperature between the interior TP and the eastern edges of the plateau at same altitude are calculated as the measurement of mass elevation effect. Leshan, Pingwu and Lintao are three stations located at the eastern edges of the plateau or neighboring lowland, and their temperatures are adjusted to the altitudes of the stations in the interior TP with Equation (1) based on the lapse rates of Mt. Emei (Table 1). The results are shown in Table 3. At the altitude of Lhasa station (3648.9 m), the minimum and maximum differences between Lhasa and Leshan are 7.3°C (July) and 11°C (June); at the altitude of Zuogong station (3780 m), the minimum and maximum differences between Zuogong and Leshan are 4.2°C (November) and 8.8°C (June). Similarly, at the altitude of Anduo station (4800 m), the minimum and maximum differences between Anduo and Pingwu are 2.0°C (November) and 6.8°C (June); at the altitude of Seda station (3893.9 m), the minimum and maximum differences between Seda and Pingwu are 0.5°C (November) and 4.0°C (June). At the altitude of Wudaoliang station (4612.2 m), the minimum and maximum differences between

Wudaoliang and Lintao are 1.5°C (March) and 4.2°C (January).

Table 1 Reported lapse rates of the Mt. Emei (°C/100 m)

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Lapse rate	0.51	0.53	0.56	0.57	0.60	0.60	0.55	0.56	0.54	0.53	0.55	0.49

Table 2 Temperatures and the adjusted temperatures in January and in July near the locations of MABs along the three W-E profiles

Profiles	MAB sites	Longi- tude	Lati- tude	Altit- ude (m)	Air tem- perature in Jan. (°C)	Air tem- perature in July (°C)	Adjusted height (m)	Adjusted air tem- perature in Jan. (°C)	Adjusted air tem- perature in Jul. (°C)
Mt.Erlang- Nyainqentanglha	Langkazi-Yangzhuoyong	90.50	29.70	5292	-10.23	6.58	5292	-10.2	6.6
	Bomi-Yigong	94.62	30.17	5096	-10.08	8.12		-11.1	7.0
	Zhuka-Dongdala shady slope	98.64	29.70	4496	-5.64	10.12		-9.7	5.7
	Zhuka-Dongdala sunny slope	98.56	29.75	4050	-4.23	11.36		-10.6	4.5
	East slope of Mt. Ningjing	99.00	29.83	3455	0.46	14.98		-8.9	4.9
	South range of Shaluli	99.73	29.75	4483	-4.75	10.35		-8.9	5.9
	Mt. Gaoshi	101.00	30.03	3226	-1.91	13.37		-12.5	2.0
	Mt. Zheduo	101.80	30.10	4218	-7.37	9.46		-12.5	3.6
	South slope of Mt.Gongga	102.07	29.39	2077	-2.45	15.90		-12.8	-1.8
	West slope of Mt. Erlang	102.56	30.12	3199	-5.07	13.12		-18.8	1.6
	East slope of Mt. Emei	103.45	29.58	473	4.96	26.65		-21.5	0.1
Mt.Guang- guang- Tuoba Beishan	Southern Qiangtang Plateau	90.00	31.33	4943	-12.24	8.44	4943	-12.24	8.44
	Naqu-Nierong	92.17	31.63	4636	-10.18	9.96		-11.75	8.28
	Shady slope of Biru-Baqing	94.59	31.50	4417	-8.79	9.85		-11.48	6.95
	Lancang River: Angqu-Shangka	96.84	31.45	3605	-3.47	13.73		-10.29	6.37
	Lancang River: Changdu	97.17	31.45	3533	-5.84	12.78		-13.03	5.03
	Lancang River: Zhaqu-Weng Dagang	97.21	31.52	3675	-2.31	13.89		-8.78	6.92
	East slope of Beishanin Tuoba	97.97	31.53	4321	-9.02	9.22		-12.19	5.80
	Xinlong of Mt. Daxueshan	100.31	30.94	3189	-4.21	12.62		-13.15	2.98
	Songlinkou-Daofu of Mt. Daxue	101.12	30.98	2934	-2.18	15.82		-12.42	4.77
	Big/small Jinchuan	102.06	31.48	2540	-0.02	17.60		-12.28	4.38
	Mt. Siguliang	102.90	31.10	3950	-10.54	11.90		-15.60	6.44
	Mt. Balang	103.17	31.07	4047	-7.63	7.89		-12.20	2.96
	South slope of Dabanzhao	103.05	31.67	3794	-11.93	11.16		-17.79	4.84
	Mt. Guangguang	103.61	31.01	745	5.61	25.53		-15.80	2.44
	Small Zhaizigou	103.80	31.35	3392	-5.10	13.64		-13.01	5.11
Mt.Wutai- Amugang	Shady slope of Memar Tso Xishan	81.83	34.45	5090	-14.31	8.30	5742	-17.64	4.71
	Sunny slope of Memar Tso Xishan	82.38	34.28	5282	-14.24	7.62		-16.59	5.09
	East slope of Amugang	85.50	33.50	5742	-17.99	5.15		-17.99	5.15
	Tanggula Mts.	89.92	33.20	5018	-13.86	8.50		-17.55	4.52
	Qumalai County	95.78	34.13	4149	-11.30	11.10		-19.42	2.34
	Shady slope of Hutou Shan	103.22	34.07	2471	-9.23	17.00		-25.92	-0.99
	Xuebaoding	103.62	32.88	3723	-9.32	10.22		-19.62	-0.88

Shady slope of Mt. Tutai	103.70	33.07	3622	−11.47	11.16		−22.28	−0.50
--------------------------	--------	-------	------	--------	-------	--	--------	-------

Table 3 Temperature and temperature differences of typical observation stations between the main plateau and surrounding areas (°C)

Stations	Lat.	Long.	Elev.(m)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Lhasa	29.7	91.1	3648.9	0.6	3.0	6.3	8.7	12.7	16.1	16.5	16.1	14.2	9.7	4.0	0.8
Zuogong	29.7	97.8	3780	−3.9	−1.9	1.5	5.0	8.7	13.0	13.3	12.8	10.9	6.2	0.0	−3.4
Leshan	29.6	103.8	424.2	7.4	10.7	14.3	19.0	22.4	24.4	26.9	26.0	22.8	18.3	14.2	8.7
T _{Lhasa-Leshan}			3648.9	9.7	9.4	10.1	8.2	9.6	11.0	7.3	8.2	8.9	8.4	7.5	7.8
T _{Zuogong-Leshan}			3780	5.9	5.2	6.0	5.1	6.4	8.8	4.8	5.6	6.2	5.6	4.2	4.3
Anduo	32.4	91.1	4800	−12.3	−10.4	−6.4	−2.1	2.0	6.0	8.4	8.2	5.3	−1.2	−8.5	−11.3
Seda	32.3	100.3	3893.9	−9.6	−6.7	−3.0	1.6	4.9	8.7	10.7	10.1	7.3	1.7	−5.2	−8.4
Pingwu	32.4	104.5	893.2	4.7	7.9	11.7	16.2	19.8	22.7	24.8	23.3	19.6	15.4	10.9	5.5
T _{Anduo-Pingwu}			4800	2.9	2.4	3.8	4.0	5.6	6.8	5.1	6.7	6.8	4.1	2.0	2.4
T _{Seda-Pingwu}			3893.9	0.9	1.3	2.1	2.5	3.1	4.0	2.4	3.6	3.9	2.2	0.5	0.8
Wudaoliang	35.2	93.1	4612.2	−15.3	−13.0	−9.6	−4.5	−0.8	3.1	6.7	6.2	2.7	−4.3	−11.0	−14.1
Lintao	35.4	103.9	1893.8	−5.7	−0.7	4.2	9.5	13.7	17.1	19.3	18.7	13.8	8.3	1.7	−4.5
T _{Wudaoliang-Lintao}			4612.2	4.2	2.1	1.5	1.5	1.8	2.3	2.3	2.7	3.5	1.8	2.2	3.7

Yao and Zhang (2014) calculated the air temperature differences at the altitude of 4500 m between the main plateau and the adjacent lowlands or at the eastern edges. 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 (Table 4). In short, monthly mean air temperature in the main plateau is approximately 2–7°C higher than in the surrounding mountains and adjacent lowland areas. This analysis verifies that the main plateau is warmer than its surroundings and adjacent lowland areas at the plateau surface elevation and gives rise to so-called “mass elevation effect” of the plateau.

Table 4 Monthly temperatures and temperature differences (ΔT) between the main plateau and the surrounding/adjacent lowland areas at an altitude of 4500 m (°C)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
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 Mts.	−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 Mts.	−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 TP-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 TP-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 TP-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

Note: cited from Yao and Zhang (2014).

5.3 Implication of mass elevation effect for the MABs/treelines

On both global and continental scales, temperature is, to a great extent, the final factor for determining treeline altitude and the MABs (Holtmeier and Broll, 2005). It has been also proved that the warmest month 10°C isotherm and the warmth index of 15°C·month coincide quite well with alpine treelines, especially in temperate areas (Troll, 1973; Ohsawa, 1990). The warmest month 10°C isotherm is below 4000 m in the Qilian Mts. and the eastern edges of the plateau, and ascends to 4000–4600 m in the Hengduan Mts. It goes up to 4600–4700 m westward in Zuogong and Lhasa and even up to 5000–6000 m westward in the areas of Ga'er-Gêrzê (Figure 3). Warmth index of 15°C·month occurs above the altitude of 4500 m in the Hengduan Mts. and the southern and central parts of the plateau.

The analysis above shows that air temperature is warmer in the interior than at the eastern edges of the plateau at given elevation due to its mass elevation effect. That explains why treelines are 1000–1500 m higher in the interior than in its outer slopes and surrounding areas of the TP.

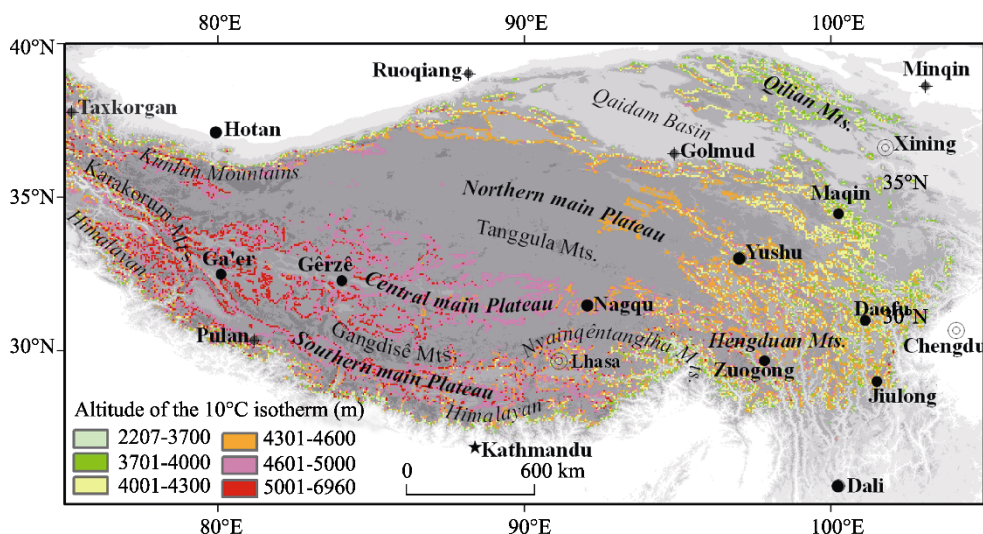


Figure 3 Spatial distribution of the 10°C isotherm for the warmest month on the Tibetan Plateau

6 Discussion and conclusions

6.1 Discussion

(1) Precipitation is also significant for the distribution of treelines and MABs

Although the warmest month 10°C isotherm is at the highest elevation of 5000–6000 m in Ga'er-Gêrzê of the southwestern TP and the highest warmth index occurs in the central TP, the highest treeline in the Northern Hemisphere does not occur in the central or the southwestern TP but in the southeastern plateau. This is because tree growth requires a certain amount of annual precipitation, at least 500 mm in plain areas and 300 mm in some high mountains (Hou, 1982). In the southwest, north and heartland of the TP, the annual precipitation is only about 50–300 mm (Liao, 1990; Zheng and Li, 1990; Zhang *et al.*, 2002; Wang *et al.*, 2011). It amounts to 500–1000 mm in the southeastern part of the plateau. As a

result, the highest treeline in the Northern Hemisphere occurs in the southeastern TP.

(2) Temperature lapse rate on the TP needs in-depth study

When studying mountain climates, temperature lapse rate is typically a necessary parameter (Rolland, 2003). However, there are few reports regarding the seasonal variation in lapse rates on TP. In this study, lapse rates measured on Mt. Emei were used for temperature adjustment calculations in the Sichuan Basin according to the reported references (Table 1). Strictly speaking, the lapse rate of Mt. Emei cannot be representative for the whole TP. Lapse rates on the TP may be smaller than that of Mt. Emei due to its MEE, and temperature lapse rates are usually steeper on isolated mountains near the sea than within extensive mountain ranges that provide their own heating (Hastenrath, 1968; Flenley, 1995). It has also been noted that lapse rates exhibit considerable variability in relation to the climatic zone, season (Hastenrath, 1968), air mass types (Yoshino, 1966) and local topography (Flenley, 2007; Barry, 2008). Thus monthly mean lapse rates on the TP and their spatiotemporal variation deserve a closer examination in the future.

(3) Comparative studies of mass elevation effect and its implications for MABs are necessary

Any massive mountains or plateaus must have great MEE. But the magnitude of MEE varies from mountain to mountain, and its implication differs for MABs and treelines in different regions. The highest snowline and treeline occur on the TP for the Northern Hemisphere, and in the central Andes for the Southern Hemisphere. The TP and the central Andes must have the greatest MEE. So, comparative studies of mass elevation effect and its implications for MABs will help disclose the mechanism of interactions between mountain complex ecological patterns and mass elevation effect.

6.2 Conclusions

(1) Due to MEE, air temperature is higher in the interior TP than in eastern edges at given elevations. At the average height (4500 m) of the TP, air temperatures are 3.58 (in April)–6.63°C (in June) higher in the interior TP than in the Sichuan Basin. The 10°C isotherm of the warmest month goes upward from the eastern border to the interior of the plateau, e.g., 4000 m in the Qilian Mts. and up to 4600–5000 m in Lhasa and Zuogong. Warmth index at an altitude of 4500 m in the interior TP can be up to over 15°C·month, but lower than 15°C·month at the same elevation at the eastern edges of the TP.

(2) Air temperature, MABs and treelines follow a similar trend of rising inwards due to MEE. Dark coniferous forest is 1000–1500 m higher, alpine steppe belts 700–900 m higher, and treelines 1000–1500 m higher in the interior plateau than at the eastern edges.

References

- Barry R G, 2008. Mountain Weather and Climate. Boulder, USA: Cambridge University Press.
- Chen Longxun, Reiter E R, Feng Zhiqiang, 1985. The atmospheric heat-source over the Tibetan Plateau: May–August 1979. *Monthly Weather Review*, 113: 1771–1790.
- De Quervain A, 1904. Die Hebung der atmosphärischen Isothermen in den Schweizer Alpen und ihre Beziehung zu den Höhengrenzen. *Gerlands Beiträge zur Geophysik*, 6: 481–533
- Flenley J R, 1995. Cloud forest, the Massenerhebung effect, and ultraviolet insolation. *Ecological Studies*, 110:

150–155.

- Flohn H, 1951. Some remarks on the annual trend of weather in the Scottish highlands. *Quarterly Journal of the Royal Meteorological Society*, 77(334): 674–675.
- Flohn H, 1957. Large-scale aspects of the “summer monsoon” in South and East Asia. *Journal of the Meteorological Society of Japan*, 75: 180–186.
- Grubb P J, 1971. Interpretation of Massenerhebung effect on tropical mountains. *Nature*, 229(5279): 44–45.
- Han Fang, Yao Yonghui, Dai Shibao *et al.*, 2012. Mass elevation effect and its forcing on timberline altitude. *Journal of Geographical Sciences*, 22(4): 609–616.
- Hastenrath S, 1968. Certain aspects of the three-dimensional distribution of climate and vegetation belts in the mountains of Central America and southern Mexico. *Colloquium Geography*, 9: 122–130.
- Hoch G, Körner C, 2005. Growth, demography and carbon relations of *Polylepis* trees at the world's highest treeline. *Function of Ecology*, 19(6): 941–951.
- Holtmeier F K, 2003. Mountain Timberlines: Ecology, Patchiness, and Dynamics. Dordrecht, Boston: Kluwer Academic Publishers.
- Hou Xueyu, 1982. China Vegetation Geography and Dominant Plant Composition. Beijing: Science Press. (in Chinese)
- Li Qiaoyuan, Xie Zichu, 2006. Analyses on the characteristics of the vertical lapse rates of temperature: Take Tibetan Plateau and its adjacent area as an example. *Journal of Shihezi University (Natural Science)*, 24(6): 719–723. (in Chinese)
- Liao Ke, 1990. The Atlas of the Tibetan Plateau. Beijing: Science Press. (in Chinese)
- Liu Dongshen, Sun Honglie, Zheng Du, 2003. The Tibet Plateau research's scientific paradigm, effect and its spiritual connotation. <http://www2.cas.cn/html/Dir/2003/10/14/2458.htm>. (in Chinese)
- Liu Kaifa, 1992. Climate of the Emei Shan. *Journal of Mianyang Agricultural College*, 9(3): 44–48. (in Chinese)
- Miehe G, Miehe S, Vogel J *et al.*, 2007. Highest treeline in the Northern Hemisphere found in southern Tibet. *Mountain Research and Development*, 27(2): 169–173.
- Ohsawa M, 1990. An interpretation of latitudinal patterns of forest limits in South and East Asian mountains. *Journal of Ecology*, 78(2): 326–339.
- Shi Yafeng, Zheng Benxing, Li Shijie, 1992. Last Glaciation and Maximum Glaciation in the Qinghai-Xizang (Tibet) Plateau: A controversy to M. Kuhle's ice sheet hypothesis. *Chinese Geographical Science*, 2(4): 293–311.
- Sun Ranhao, Zhang Baiping, 2008. Exploring the method of digital identification of mountain altitudinal belts. *Geoinformation Science*, 10(6): 690–696. (in Chinese)
- Sun Ranhao, Zhang Baiping, Tan Jing, 2008. A multivariate regression model for predicting precipitation in the Daqing Mountains. *Mountain Research and Development*, 28(3): 318–325.
- Tollner H, 1949. Der Einfluß großer Massenerhebungen auf die Lufttemperatur und die Ursachen der Hebung der Vegetationsgrenzen in den inneren Ostalpen. *Theoretical and Applied Climatology*, 1(3): 347–372.
- Troll C, 1973. The upper timberlines in different climatic zones. *Arctic and Alpine Research*, 5(3): 3–18.
- Wang Chuanhui, Zhou Shunwu, Tang Xiaoping *et al.*, 2011. Temporal and spatial distribution of heavy precipitation over Tibetan Plateau in recent 48 years. *Scientia Geographica Sinica*, 31(4): 470–477. (in Chinese)
- Wu Guoxiong, Liu Yiming, Liu Xin *et al.*, 2005. How the heating over the Tibetan Plateau affects the Asian climate in summer. *Chinese Journal of Atmospheric Sciences*, 29(1): 47–57. (in Chinese)
- Wu Zhangwen, 1996. Local climate measurement of Qingcheng Shan. *Journal of Sichuan Forestry Science and Technology*, 17(1): 74–76. (in Chinese)
- Yao Yonghui, Zhang Baiping, 2013a. A preliminary study of the heating effect of the Tibetan Plateau. *PLOS One*. doi: 10.1371/journal.pone.0068750.
- Yao Yonghui, Zhang Baiping, 2013b. MODIS-based estimation of air temperature of the Tibetan Plateau. *Journal of Geographical Sciences*, 23(4): 627–640.
- Yao Yonghui, Zhang Baiping, 2013c. MODIS-based estimation of air temperature and heating effect of the Tibetan Plateau. *Acta Geographica Sinica*, 68(1): 93–104. (in Chinese)
- Yao Yonghui, Zhang Baiping, 2014. The mass elevation effect of the Tibetan Plateau and its implications for Alpine

- treelines. *International Journal of Climatology*. doi: 10.1002/joc.4123.
- Ye Duzheng, 1982. Some aspects of the thermal influences of Qinghai-Tibetan Plateau on the atmospheric circulation. *Archives for Meteorology, Geophysics, and Bioclimatology*, 31(3): 205–225.
- Ye Duzheng, Luo Siwei, Zhu Baozhen, 1957. The flow pattern and heat budget in the troposphere over the Tibetan Plateau and surrounding area. *Acta Meteorologica Sinica*, 28(2): 108–121. (in Chinese)
- Zhang Baiping, 2008. Progress in the study on digital mountain altitudinal belts. *Journal of Mountain Science*, 26(1): 12–14. (in Chinese)
- Zhang Baiping, Chen Xiaodong, Li Baolin *et al.*, 2002. Biodiversity and conservation in the Tibetan Plateau. *Journal of Geographical Sciences*, 12(2): 135–143.
- Zhang Baiping, Tan Jing, Yao Yonghui, 2009. Digital Information and Patterns of Mountain Altitudinal Belts. Beijing: China Environmental Sciences Press. (in Chinese)
- Zhao Fang, Zhang Baiping, Tan Jing *et al.*, 2011. Structure and function of the digital integrated system for the Eurasian mountain altitudinal belt. *Journal of Geo-information Science*, 13(3): 346–355. (in Chinese)
- Zhao Y, Li H J, Huang A N *et al.*, 2013. Relationship between thermal anomalies in Tibetan Plateau and summer dust storm frequency over Tarim Basin, China. *Journal of Arid Land*, 5(1): 25–31.
- Zheng Du, Li Bingyuan, 1990. Evolution and differentiation of the natural environment of the Qinghai-Tibet Plateau. *Geographical Research*, 9(2): 1–10. (in Chinese)
- Zheng Yuanchang, Gao Shenghuai, Chai Zongxin, 1986. A preliminary study on the vertical natural zones in the Hengduan Mountainous region. *Mountain Research*, 4(1): 75–83. (in Chinese)