

Magnitude and Forming Factors of Mass Elevation Effect on Qinghai-Tibet Plateau

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Abstract: Mass elevation effect (MEE) refers to the thermal effect of huge mountains or plateaus, which causes the tendency for temperature-related montane landscape limits to occur at higher elevations in the inner massifs than on their outer margins. MEE has been widely identified in all large mountains, but how it could be measured and what its main forming-factors are still remain open. This paper, supposing that the local mountain base elevation (MBE) is the main factor of MEE, takes the Qinghai-Tibet Plateau (QTP) as the study area, defines MEE as the temperature difference (ΔT) between the inner and outer parts of mountain massifs, identifies the main forming factors, and analyzes their contributions to MEE. A total of 73 mountain bases were identified, ranging from 708 m to 5081 m and increasing from the edges to the central parts of the plateau. Climate data (1981–2010) from 134 meteorological stations were used to acquire ΔT by comparing near-surface air temperature on the main plateau with the free-air temperature at the same altitude and similar latitude outside of the plateau. The ΔT for the warmest month is averagely 6.15°C, over 12°C at Lhatse and Baxoi. A multivariate linear regression model was developed to simulate MEE based on three variables (latitude, annual mean precipitation and MBE), which are all significantly correlated to ΔT . The model could explain 67.3% of MEE variation, and the contribution rates of three independent variables to MEE are 35.29%, 22.69% and 42.02%, respectively. This confirms that MBE is the main factor of MEE. The intensive MEE of the QTP pushes the 10°C isotherm of the warmest month mean temperature 1300–2000 m higher in the main plateau than in the outer regions, leading the occurrence of the highest timberline (4900 m) and the highest snowline (6200 m) of the Northern Hemisphere in the southeast and southwest of the plateau, respectively.

Keywords: Qinghai-Tibet Plateau; mass elevation effect (MEE); temperature difference; mountain base elevation; timberline

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1 Introduction

Mass elevation effect (MEE) refers to the thermal effect of huge mountains or plateaus, which causes temperature in these massifs higher than free atmosphere at same elevations in its surrounding areas, leading to the tendency for temperature-related montane landscape limits to occur at higher elevations in the inner massifs than on their outer margins (Quervain, 1904). It is one of the main factors influencing the distribution of alti-

tudinal belts on the large scale and it even serves as the important mechanism for the spatial patterns and dynamics of the earth surface systems (Zhang *et al.*, 2009). It has been explored in many disciplines including geography, ecology and climatology (Grubb, 1971; Bruijnzeel *et al.*, 1993; Fang *et al.*, 1999; Zheng, 2001; Barry, 2008; Holtmeier, 2009), and many efforts have been made to explain this phenomenon. It is believed that large massifs receive more radiation than surrounding atmosphere, and the air in the massifs is heated

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through the combined effect of radiation, sensible heat and the latent heat (Tollner, 1949; Flohn, 1968). Consequently, air temperature is higher in the inner mountain massifs than in the free atmosphere at any given elevation (Holtmeier, 2009). However, current research on MEE is still at a stage of qualitative description; we still don't know how it could be measured, and what its main forming factors are.

The immense and towering QTP has a strong thermal effect (Yeh *et al.*, 1957; Chen *et al.*, 1985), and is a significant heating source of the world in summer (Flohn, 1968; Yeh and Chang, 1974). This paper takes the plateau and its surrounding areas as the study area, defines MEE as the temperature difference (ΔT) on same elevation between the inner and outer parts of QTP, identifies the main MEE forming factors, and analyzes their contribution rates to MEE.

2 Methods

2.1 Study area

The study area is located between latitudes 25°N and 40°N and longitudes 70°E and 109°E (Fig. 1), including the whole QTP and its neighboring areas. The QTP is the largest and highest plateau on the Earth, about $2.5 \times 10^6 \text{ km}^2$ and averagely 4500 m in height. Climatically, it is warm-humid in the southeast and cold-arid in the northwest; accordingly, montane conifer forest, alpine meadow, alpine steppe and alpine desert occur successively from southeast to northwest (Zheng and Li, 1990b). Around QTP are generally low lands, for exam-

ple, the Sichuan Basin to the east of the plateau is below 1000 m above sea level.

2.2 Data sources

The monthly climate data (air temperature and precipitation, 1981 to 2010) for 134 meteorological stations (Fig. 1) are compiled from the China Meteorological Information Center (<http://cdc.cma.gov.cn/index.jsp>) for 130 stations, and from the Global Historical Climatology Network-Monthly (GHCN-M) (Menne *et al.*, 2012) for the other four stations. Of those 134 stations, 105 (Table 1) are located in the plateau, and 29 (Table 2) in the surrounding areas of QTP.

ASTER Global Digital Elevation Model (GDEM) data with a spatial resolution of 30 m were downloaded from <http://asterweb.jpl.nasa.gov/gdem.asp>. Missing values in the data set were replaced with the mean of the adjacent 3×3 pixels.

Generally, temperature lapse rate (TLR) is a necessary parameter when studying mountain climate (Rolland, 2003). Li and Xie (2007) estimated the TLR in July of the surrounding areas of the QTP based on elevation and temperature of isobaric surfaces, and the results were very close to the estimation by other scholars (Xie and Zeng, 1983; Huang, 1994; Ye *et al.*, 1997; Zhang, 1998), only with some little differences in the very complex Hengduan Mountains, e.g. the TLR is about $0.65^\circ\text{C}/100 \text{ m}$ at Baima Snow Mountain according to Li and Xie (2007), while around $0.7^\circ\text{C}/100 \text{ m}$ according to Zhang (1998). So, we suppose that the TLR from Li and Xie (2007) is reliable and could be used in our study.

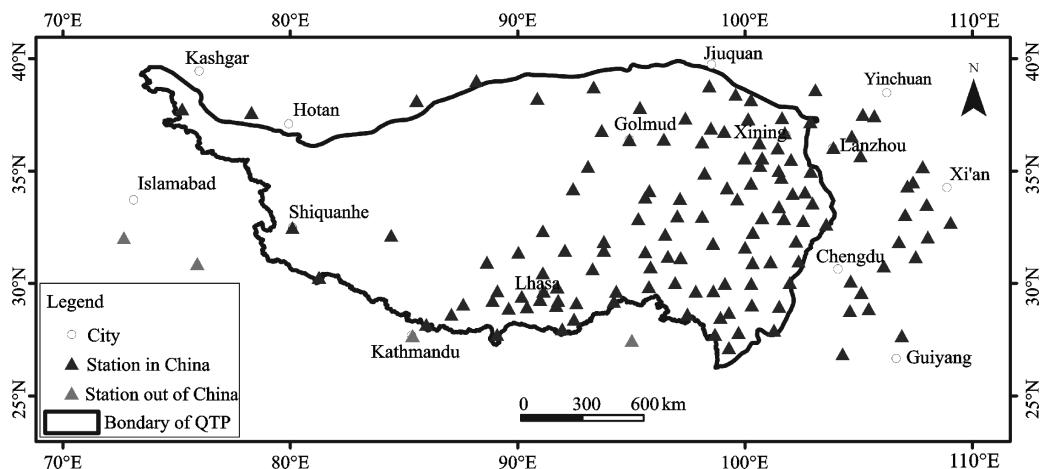


Fig. 1 Sketch map of Qinghai-Tibet Plateau (QTP) and location of the 134 meteorological stations

Table 1 Data for 105 meteorological stations in Qinghai-Tibet Plateau

Name	Latitude (°)	Longitude (°)	Elevation (m)	MTWM (°C)	AP (mm)	MBE (m)	Name	Latitude (°)	Longitude (°)	Elevation (m)	MTWM (°C)	AP (mm)	MBE (m)	Name	Latitude (°)	Longitude (°)	Elevation (m)	MTWM (°C)	AP (mm)	MBE (m)
Taskorgan	37.77	75.23	3075	16.61	160	3721	Nyingchi	29.67	94.33	3040	16.23	691	2894	Zhongdian	27.83	99.70	3279	13.91	781	2064
Shiquanhe	32.50	80.08	4289	14.57	81	4311	Golmud	36.42	94.90	2808	18.74	81	2889	Xinghai	35.58	99.98	3301	12.79	382	2751
Burang	30.28	81.25	4778	14.51	156	3155	Zadoi	32.90	95.30	4154	11.34	533	4618	Garze	31.62	100.00	3377	14.28	630	4284
Gerze	32.15	84.42	4769	12.88	236	4768	Da Qaidam	37.85	95.37	3196	16.53	96	2889	Gangea	37.33	100.13	3314	11.44	374	3217
Nie Lal	28.18	85.97	4319	10.92	451	3498	Zhidoi	33.85	95.60	4192	9.19	447	4386	Qilian	38.18	100.25	2720	13.58	412	1270
Tingri	28.63	87.08	4476	12.28	383	3498	Denggen	31.42	95.60	3934	12.68	615	3785	Golog	34.47	100.25	3732	10.40	533	4073
Lhatse	29.98	87.60	4365	14.37	395	4296	Bome	29.87	95.77	2745	16.99	724	2894	Litang	30.00	100.27	3974	11.05	695	4254
Xainza	30.95	88.63	4652	10.08	390	4722	Qumarleb	34.13	95.78	4186	9.41	491	46.8	Daocheng	29.05	100.30	3760	12.25	672	4254
Shigatse	29.25	88.88	3844	14.54	418	4296	Lhorong	30.75	95.83	3777	14.96	583	4042	Xinlong	30.93	100.32	3078	15.19	650	4254
Phag Ri	27.73	89.08	4365	8.15	422	3498	Nuomuhong	36.43	96.42	2798	18.23	125	2889	Sertar	32.28	100.33	3926	10.34	660	4284
Namling	29.68	89.10	4003	13.71	456	4296	Nangqen	32.20	96.48	3630	13.85	517	3685	Qabqa	36.27	100.62	2817	16.16	361	2751
Gyantse	28.92	89.60	4022	12.67	342	4296	Riwoqe	31.22	96.60	3804	12.48	517	3785	Tongde	35.27	100.65	3280	11.70	445	2751
Baingoin	31.38	90.02	4723	9.20	425	4651	Baxoi	30.05	96.92	3377	19.48	463	4127	Guinan	35.58	100.75	3102	14.52	412	2751
Nyemo	29.43	90.17	3819	14.95	442	4296	Yushu	33.02	97.02	3947	13.51	525	4386	Bannna	32.93	100.75	3704	12.23	663	3450
Nagare	28.97	90.40	4471	10.46	365	4496	Qingshuive	33.80	97.13	4426	7.04	473	4548	Dawu	30.98	101.12	2960	16.11	687	4254
Mangnai	38.25	90.85	2946	16.72	49	2889	Chamdo	31.15	97.17	3360	16.37	515	3685	Mili	27.93	101.27	2624	18.41	802	2465
Gonggar	29.30	90.98	3569	16.50	459	3680	Delhi	37.37	97.37	2987	17.15	210	2889	Guide	36.03	101.43	2242	18.92	368	1484
Amdo	32.35	91.10	4697	8.19	446	4651	Zayu	28.65	97.47	2972	19.06	793	3592	Zekog	35.03	101.47	3652	8.81	497	3450
Damxung	30.48	91.10	4281	11.31	484	4296	Zogang	29.67	97.83	4262	13.11	596	4257	Jigzhi	33.43	101.48	3625	10.67	655	3450
Lhasa	29.67	91.13	3655	16.27	482	3680	Dulan	36.30	98.10	3188	15.35	243	2889	Jiulong	29.00	101.50	3158	15.33	859	3104
Qonggyai	29.03	91.68	3748	15.54	454	3680	Serxu	32.98	98.10	4261	8.99	523	4284	Henan	34.73	101.60	3519	10.45	565	3450
Maizhokunggar	29.85	91.73	3810	14.15	532	3680	Madoi	34.92	98.22	4271	8.10	362	4221	Menyuan	37.38	101.62	2881	12.72	472	1484
Tsetang	29.25	91.77	3558	16.38	459	3680	Tuole	38.80	98.42	3368	11.14	317	3514	Aba	32.90	101.70	3271	12.64	672	3450
Cona	27.98	91.95	4409	8.13	374	3498	Wulan	36.92	98.48	2962	16.45	234	2889	Xining	36.72	101.75	2317	17.41	390	1484
Nagqu	31.48	92.07	4516	9.60	517	4651	Dege	31.80	98.58	3577	14.89	628	3824	Kangding	30.05	101.97	2826	15.79	770	3104
Tuotuhe	34.22	92.43	4535	8.19	342	4618	Markam	29.68	98.60	3893	12.12	570	4386	Tongren	35.52	102.02	2503	17.32	435	1484
Lhunze	28.42	92.47	3907	13.49	368	3498	Gongshan	27.75	98.67	1508	21.46	1149	2889	Mequ	34.00	102.08	3478	11.55	633	3450
Gyaca	29.15	92.58	3241	16.92	520	3083	Deqen	28.48	98.92	3197	13.20	796	2807	Barkam	31.90	102.23	2853	16.42	732	3450
Wudaoliang	35.22	93.08	4614	6.20	285	4548	Chaka	36.78	99.08	3090	14.43	259	2751	Xiaojin	31.00	102.35	2274	19.86	753	2199
Lhari	30.67	93.28	5381	8.86	672	4296	Batang	30.00	99.10	2531	19.75	566	3103	Hongyuan	32.80	102.55	3490	11.27	728	3450
Lenghu	38.75	93.33	2779	17.96	21	2889	Zhongxinzhhan	34.27	99.20	4212	7.25	476	4221	Langmusi	34.08	102.63	3420	10.59	615	3450
Xiaozhaohuo	36.80	93.68	2773	18.10	62	2889	Derong	28.72	99.28	2489	21.43	576	3103	Wushaoling	37.20	102.87	3034	12.01	425	1484
Sog	31.88	93.78	4023	11.92	630	4651	Weixi	27.17	99.28	2413	18.80	925	1960	Hezuo	35.00	102.90	2944	13.35	500	1484
Biwu	31.48	93.78	4158	12.77	660	4651	Yeningou	38.42	99.58	3219	9.89	400	1270	Zoige	33.58	102.97	3463	11.30	627	3450
Mainling	29.22	94.22	3093	16.30	749	3083	Darlag	33.75	99.65	3983	9.81	555	4221	Songpan	32.65	103.57	3283	14.94	673	2199

Notes: MTWM means Mean Temperature of the Warmest Month; AP means Annual Precipitation; MBE means Mountain Base Elevation.

Table 2 Data for 29 meteorological stations in neighboring areas of Qinghai-Tibet Plateau

Name	Latitude (°)	Longitude (°)	Elevation (m)	Slope (°)	MTWM (°C)	TLR (°C/100 m)
Sargodha (Pakistan)	32.05	72.67	188	0.26	32.08	0.60
Ludhiana (India)	30.90	75.90	247	2.87	30.00	0.50
Pishan	37.62	78.28	1374	0.58	25.82	0.83
Kathmandu (Nepal)	27.70	85.37	1337	3.69	24.59	0.65
Qiendo	38.15	85.55	1245	2.71	25.83	0.77
Ruoqiang	39.03	88.17	885	1.21	28.08	0.77
Dibrugarh (India)	27.48	95.02	111	0.88	28.00	0.65
Minqin	38.63	103.08	1367	0.35	23.80	0.85
Lanzhou	36.05	103.88	1516	0.63	22.95	0.62
Weining	26.87	104.28	2200	0.82	17.80	0.53
Yibin	28.80	104.60	328	0.59	27.11	0.65
Ziyang	30.12	104.65	363	0.52	26.31	0.65
Jingyuan	36.57	104.68	1406	1.56	22.87	0.61
Huinong	35.68	105.08	1899	1.18	18.70	0.60
Neijiang	29.62	105.12	327	2.37	27.01	0.65
Zhongwei	37.53	105.18	1225	0.12	23.09	0.68
Luzhou	28.88	105.43	297	6.96	26.88	0.65
Zhongning	37.48	105.68	1186	0.37	23.93	0.73
Nanchong	30.78	106.10	277	2.46	27.51	0.60
Bazhong	31.87	106.77	381	1.11	27.16	0.65
Zunyi	27.70	106.88	857	2.97	25.39	0.53
Hanzhong	33.07	107.03	510	1.42	25.90	0.60
Baoji	34.35	107.13	597	0.48	25.83	0.65
Fengxiang	34.52	107.38	787	0.96	24.45	0.65
Daxian	31.20	107.50	292	1.99	27.65	0.65
Changwu	35.20	107.80	1187	1.16	22.05	0.60
Foping	33.52	107.98	828	2.79	22.76	0.60
Wanyuan	32.07	108.03	650	1.41	25.20	0.68
Ankang	32.72	109.03	271	7.17	27.27	0.58

Notes: MTWM means mean temperature of the warmest month; TLR means temperature lapse rate

2.3 Mass elevation effect forming factors

In mountain areas, the distribution of heat is mainly determined by latitude, altitude, precipitation and topography (Barry, 2008). In other words, they serve as the main factors of MEE. Latitude is usually taken as the surrogate of solar radiation reaching the ground, altitude can determine the vertical distribution of heat by affecting state of the atmosphere and radiation components, and annual mean precipitation can affect the heat budget of the earth-atmosphere system, and further influence the distribution of temperature in mountains by affecting surface albedo (Xie, 1984) and hygric continentality (Gams, 1931).

Mountain base elevation (MBE) is the average elevation of the local bases from where mountains or plateaus

uplift (Shreve, 1922; Zhang *et al.*, 2012). It can describe the structure and characteristics of mountain topography by its boundary, shape and elevation. For sensible heat and latent heat, the main sources of heat of the atmosphere near the ground, are mainly determined by topography (Weng and Luo, 1990), MBE can reflect the effect of terrain factors on the accumulation and redistribution of heat in mountains. MBE can be used to evaluate the heat conditions vertically through the elevation of local bases, and is actually the starting point for mountain air temperature to decrease vertically in its relevant basin. Thus, this paper hypothesizes that MBE is the leading forming-factor of MEE. In other words, MEE should rises with the increasing of MBE. Therefore, MEE can be quantified with three factors of latitude, annual mean

precipitation and MBE.

2.4 Mass elevation effect identification

This can be done by two steps (Zhang *et al.*, 2012).

(1) Identification of local mountain basins. This is to divide the large mountain massifs into a certain number of intra-mountain basins with respect to the orientation and trend of mountain ridges and the outer boundary of MBE. The orientation and trend of mountain ridges were extracted based on DEM (Wolock *et al.*, 1995; Tang *et al.*, 2003), and the principles defined by United Nations Environment Program World Conservation Monitoring Centre (UNEP WCMC, <http://www.unep-wcmc.org/>) were adopted to acquire the mountain region which is used as outer boundary of MBE.

(2) Quantification of the base elevation of intra-mountain basins. Relief amplitude (RA) and slope is combined to quantify the base elevation with reference to the landform classification systems for China (Li, 1987; Li *et al.*, 2008; Zhou *et al.*, 2009) and for Europe (Demek and Embleton, 1978; Demek and Embleton, 1989). The procedure is as follows: 1) for different range of RA, there is a corresponding slope value to identify base areas of local basins ($RA \leq 500$ m, slope $\leq 7^\circ$; $500 \text{ m} < RA \leq 1000 \text{ m}$, slope $\leq 15^\circ$; $RA > 1000 \text{ m}$, slope $\leq 25^\circ$); 2) since the mountain base must be in the lower parts of the basin, the parts higher than the average altitude of the relevant basin should be excluded from the result; 3) the average altitude of the base is the MBE of the basin.

2.5 Quantitative analysis of Mass elevation effect and model building

MEE can be simply defined as the temperature difference between the inner and outer parts of mountain massifs at same altitude and close latitudes. That is to say, the magnitude of MEE can be acquired using the equation:

$$\Delta T = T_{\text{in}} - T_{\text{freeair}} \quad (1)$$

where ΔT is temperature difference between the inner and outer parts of mountain massifs; T_{in} is near-surface air temperature in the mountain massifs; and T_{freeair} is free-air temperature at same altitude and similar latitude out of the mountain massifs. T_{in} can be obtained from the meteorological stations inside the massifs (STN_{in}), and T_{freeair} can be calculated by the temperature and TLR

of the meteorological stations outside the massifs (STN_{out}) paired with the STN_{in} using the following equation,

$$T_{\text{freeair}} = T_{\text{out}} + (H_{\text{in}} - H_{\text{out}}) \times TLR \quad (2)$$

where T_{out} is temperature at the STN_{out} ; H_{in} and H_{out} are elevation of the station in and out of the massifs, respectively; TLR is temperature lapse rate at the STN_{out} . To minimize the influence of latitude or topography, the STN_{out} should be at the same or similar latitude with paired STN_{in} and be located on gentle terrains.

Then, a multivariate linear regression equation was developed to simulate MEE (take ΔT of QTP in July as the quantitative index) with three independent variables (latitude, annual mean precipitation and MBE).

3 Results

3.1 Mass elevation effect of Qinghai-Tibet Plateau

First, identify the mountain region and the main ridge-lines (Fig. 2). Then, take the mountainous border as the outer boundary of MBE, and divide this area into different local basins by the main ridgelines.

Finally, a total of 73 mountain local basins were identified (Fig. 3), whose base elevation ranges from 708 m to 5081 m, with a trend of rising from the edges to the central part of the plateau. The basins can depict the multi-scale terrain features of the QTP, including the shape, trend and region of the large scale terrains, relationship between interior mountains on the plateau, and landform differentiation within an individual mountain range.

3.2 Mass elevation effect for warmest month

Based on climate data from 134 stations, the ΔT of the QTP in the warmest month (July) during the period of 1981–2010 was calculated, which was averagely up to 6.15°C , over 12°C at Lhatse and Baxoi, indicating that there is a strong MEE in QTP in July of the period. The spatial pattern of ΔT shows a trend of rising from the outer areas to the central plateau (Fig. 4), similar to the distribution pattern of MBE.

3.3 Multivariate linear regression model of mass elevation effect

Correlation analysis shows that MEE correlates significantly with latitude and MBE, but weakly with annual

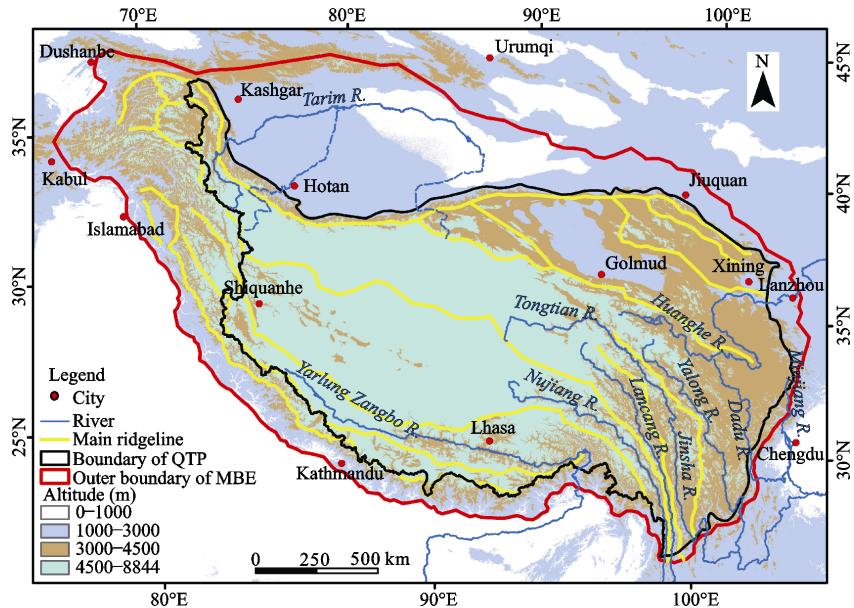


Fig. 2 Mass elevation effect (MBE) outer boundary and main ridgelines of Qinghai-Tibet Plateau (QTP)

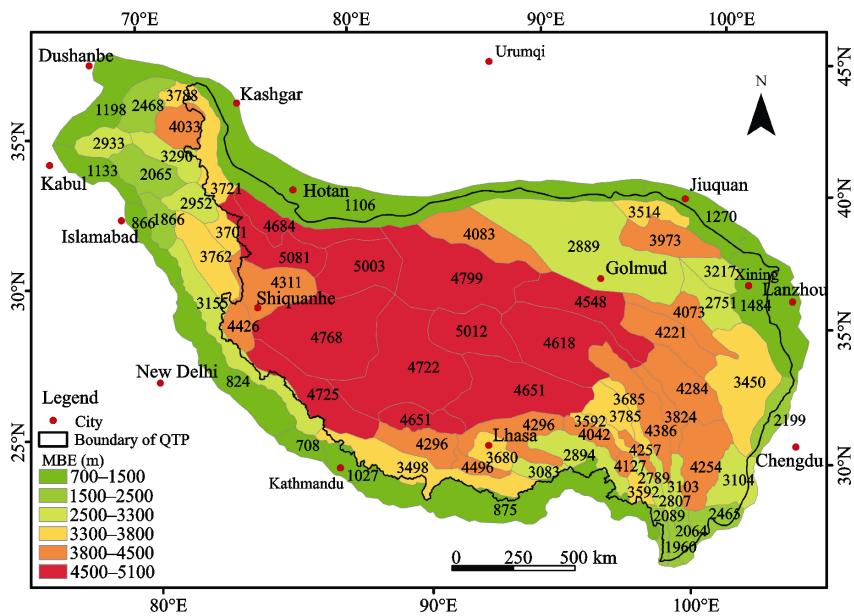


Fig. 3 Mountain Base Elevation (MBE) of Qinghai-Tibet Plateau (QTP) and its neighboring areas

mean precipitation (Table 3). It can be found that annual mean precipitation correlates with latitude. Because the moisture decreasing trend from the southeast to the northwest of the QTP is the result of natural conditions (Zheng and Li, 1990a), and the correlation coefficient is low, the variables can be considered independent.

The normal P-P plot of regression standardized residual values shows that residuals are normally distrib-

uted (Fig. 5). Coefficient of determination (R^2), Durbin-Watson statistic and F-value of analysis of variance (ANOVA) indicate that the linear regression equation could adequately fit the distribution of MEE (Table 4). Meanwhile, collinearity statistics shows that there is a lack of multicollinearity in the model, and the result of T-test demonstrates that these independent variables have significant correlations with the dependent variable (Table 4).

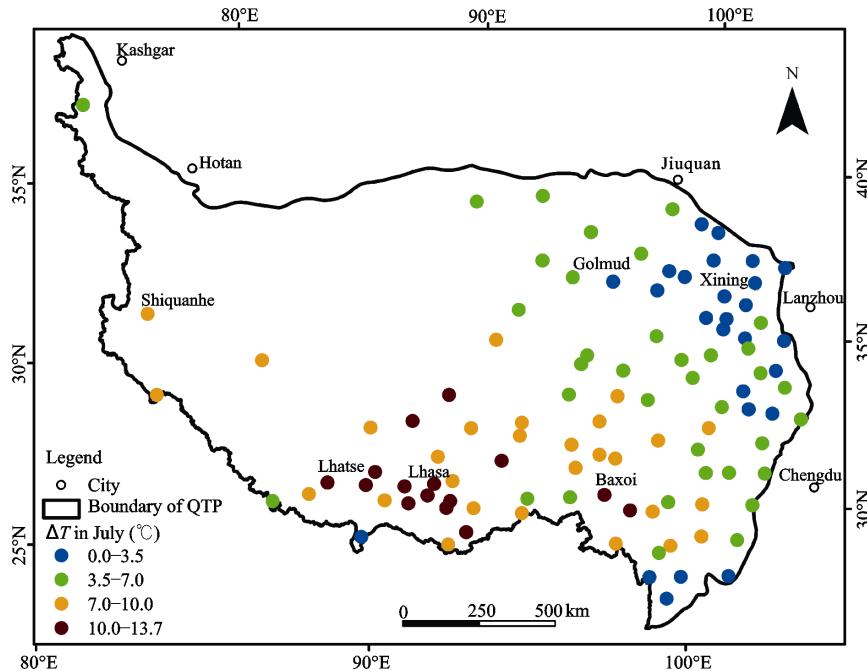


Fig. 4 Temperature difference (ΔT) distribution of Qinghai-Tibet Plateau (QTP) for July (1981–2010)

Table 3 Correlations of variables in mass elevation effect (MEE) model of Qinghai-Tibet Plateau

		Latitude	MBE	Annual mean Precipitation	MEE
Latitude	Pearson correlation	1			
	Sig. (2-tailed)	0.000			
	Sample number	105			
MBE	Pearson correlation	-0.331	1		
	Sig. (2-tailed)	-0.588	0.000		
	Sample number	105	105		
Annual mean precipitation	Pearson correlation	-0.008(*)	-0.019	1	
	Sig. (2-tailed)	0.010	0.845	0.000	
	Sample number	105	105	105	
MEE	Pearson correlation	-0.569(**)	0.693(**)	0.271(*)	1
	Sig. (2-tailed)	0.000	0.000	0.034	0.000
	Sample number	105	105	105	105

Notes: *: correlation is significant at the 0.05 level (2-tailed); **: correlation is significant at the 0.01 level (2-tailed)

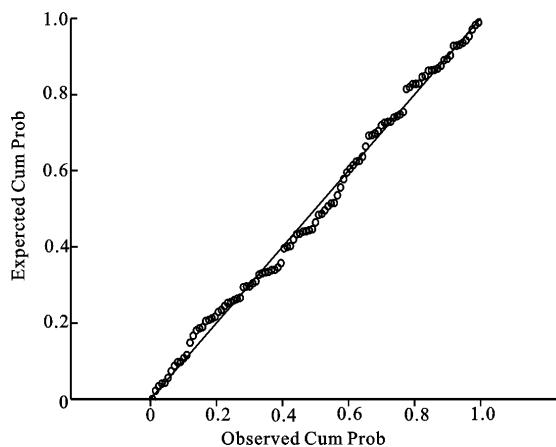


Fig. 5 Normal P-P plot of regression standardized residual (dependent variable: MEE)

The model is as follows:

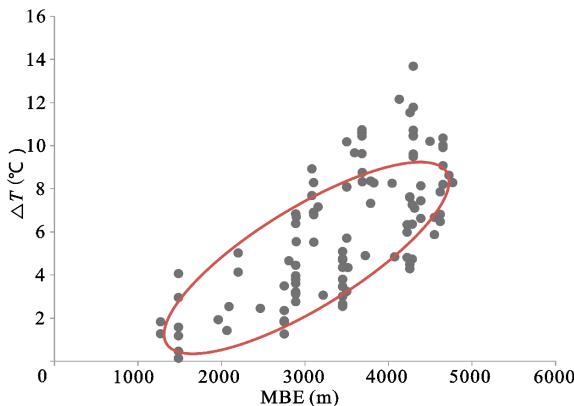
$$MEE = 0.002 \times MBE - 0.57 \times lat - 0.005 \times amp + 21.215 \quad (3)$$

where MEE is mass elevation effect of QTP in July; MBE is mountain base elevation; lat is latitude, and amp is annual mean precipitation.

In terms of the standardized regression coefficients, the contributions of three independent variables (latitude, annual mean precipitation and MBE) to MEE are 35.29%, 22.69%, and 42.02%, respectively, and MBE shows a positive relationship with MEE (Fig. 6), confirming that MBE is the key factor for the MEE formation and, to a great extent, could represent MEE.

Table 4 Summary of regression model

	Coefficient of determination (R^2)	Durbin-Watson	F	Unstandardized coefficients (B)	Standardized coefficients (Beta)	t	Sig.	Collinearity statistics		Contribution rate (%)
								Toerance	VIF	
Constant term	0.673	1.398	95.248	21.215		6.749	0.000			
MBE			($P=0.000$)	0.002	0.587	7.886	0.000	0.827	1.209	42.02
Latitude				-0.570	-0.493	-7.710	0.000	0.558	1.793	35.29
Annual mean Precipitation				-0.005	-0.317	-4.415	0.000	0.626	1.598	22.69

**Fig. 6** Relationship between mass elevation effect (MEE) (July) and Mountain Base Elevation (MBE) in Qinghai-Tibet Plateau (1981–2010)

4 Discussion and Conclusions

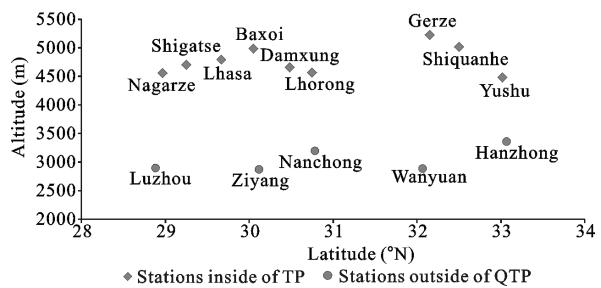
4.1 Discussion

(1) A multivariate linear regression model was developed to simulate MEE with three independent variables (MBE, latitude and annual mean precipitation). The great contribution of MBE to MEE is revealed, confirming our hypothesis that MBE is the most important factor of MEE. However, there are some defects in the calculation of ΔT and the model development. Firstly, only 29 stations outside the QTP were used to calculate ΔT (Fig. 1). So, one station outside the QTP has to correspond to more than one station inside the main plateau. This may induce some uncertainty to the result of ΔT due to differing terrain conditions and distance between paired stations. In future studies, real free-air temperature (e.g., NCAR/NCEP Reanalysis Dataset) should be used to ensure the accuracy of the results. Secondly, in this paper, only the most significant variables (latitude, MBE, annual mean precipitation) were chosen to develop MEE model. Still, there should be some more factors which may contribute to MEE, including ground surface materials, area and the relative

altitude of mountain massifs, etc. In the subsequent work, these factors should be taken into account, and stepwise multiple regression models should be adopted to deal with the multiple variables.

(2) The great MEE in the QTP virtually means that isotherms are relatively higher in the inner parts than in the outer parts of the plateau. For example, the 10°C isotherm for the July mean temperature is at altitudes of 2800–3400 m in eastern borders of the plateau, but up to 4500–5200 m in the inner parts (Fig. 7). In other words, the extraordinary MEE of QTP makes the 10°C isotherm of the warmest month approximately 1100–2400 m higher in the central than in the outer plateau. Extreme cases are the altitudinal differences of this isotherm of about 2350 m between Gerze and Wanyuan at similar latitude, and some 2111 m between Baxoi and Ziyang (Fig. 7).

It's well-known that temperature is the final factor for timberline elevation on both global and continental scales (Korner and Paulsen, 2004), and the warmest month 10°C isotherm is thought to coincide roughly with alpine timberlines in the continental high-mountains of the northern hemisphere (Ohsawa, 1990; Holtmeier, 2009). According to our analysis, it is the mass elevation effect of the plateau that pushes the 10°C isotherm upward to about 4500–5200 m above sea level, providing suitable temperature conditions for trees to live at such

**Fig. 7** Elevations of warmest month 10°C isotherm in and out of Qinghai-Tibet Plateau

elevations (Elliott and Kipfmüller, 2011). It has been found that timberlines in interior QTP are up to 4600–4700 m (Troll, 1973; Zheng *et al.*, 1990), even to 4900 m (29°42'N, 96°45'E) in the southeastern QTP, the highest timberline in the Northern Hemisphere (Miehe *et al.*, 2007), only 35 km away from Baxoi, where, as shown in Fig. 7, the warmest month 10°C isotherm is at 4984 m. The timberline is about 4450 m near Damxun (Schickhoff, 2005), where the 10°C isotherm is at altitude of 4515 m. However, to the east of the plateau, timberlines are much lower, e.g. it is at about 3300 m in the central Qinling Mountains. (Liu and Lu, 1990), where the 10°C isotherm is at 3360 m. The immense MEE of the QTP could well explain why the highest timberline of the Northern Hemisphere occurs in the southeastern QTP.

(3) The intense MEE of the plateau does not only lead to high elevation timberlines, but also high elevation snowlines. At Gerze and Shiquanhe in the western QTP, the MEE is great (the July 10°C isotherm exceed 5000 m), but no tree can grow there due to very scarce annual mean precipitation (236 mm at Gerze; 80 mm at Shiquanhe) (Liao, 1990). As we know, the prerequisites for the climatic snowline are MTWM < 7 °C, annual mean precipitation $\leq 0^\circ\text{C}$, annual precipitation ≥ 50 mm and annual solid precipitation rate $\geq 60\%$ (Jiang and Wu, 2002), and the quantitative spatial patterns of climatic snowline have been explored by relating snowline elevation with MEE using the MBE as the surrogate (Han *et al.*, 2011). We can conclude that the intense MEE of TP pushes the isotherm to a very high elevation, and gives rise to very high snowlines, about 6200 m in Mt. Nganglong Kangri (only 90 km away from Shiquanhe) in the southwest of the plateau (Tibet Expedition CaoS, 1975), which is the highest snowline in the Northern Hemisphere.

4.2 Conclusions

(1) Temperature differences (or MEE) between QTP inner and outer areas at same altitude (about 4500–5000 m) and latitude in July were calculated on the basis of climate data of 134 meteorological stations. The average MEE of the plateau is 6.15°C, with a maximum of over 12°C at Lhatse and Baxoi.

(2) MBE, latitude and annual mean precipitation are three main controlling factors of MEE. MBE contributes 42.02% to MEE of the plateau, latitude 35.29%, and

annual mean precipitation 22.69%, indicating that MBE is the most significant factor of MEE.

(3) The great MEE of TP pushes the July 10°C isotherm to a very high elevation (e.g., 4982 m at Baxoi). This could well explain why the timberline could be up to about 4900 m in the nearby areas of Baxoi in the southeastern QTP. Also due to the effect of MEE, the highest snowline (6200 m) of the Northern Hemisphere occurs in the southwestern plateau.

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