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Mass Elevation Effect and Its Contribution to the Altitude of Snowline in the Tibetan Plateau and Surrounding Areas

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Abstract

In exploring geographical distribution of mountain altitudinal belts (e.g., snowline, timber line, etc.), many unitary or dibasic fitting models have been developed to depict the relationship between altitudinal belts' elevation and longitude or latitude, or both. However, most of these models involve small scales and could not be applied to other regions, while those established for the northern hemisphere or the whole globe, are of very low precision. The reason is that these models neglect one of the most important factors controlling the distribution of altitudinal belts—mass elevation effect (*massenerhebungseffect*, short as MEE in the following text). This concept (MEE) was introduced more than 100 years ago by A. de Quervain to account for the observed tendency for temperature-related parameters such as tree line and snowline to occur at higher elevations in the central Alps than on their outer margins. Although it has been widely observed and its effect on the elevation of mountain vegetation belts recognized, this phenomenon has not been quantitatively studied. We compiled 143 snowline descriptions from literature covering the Tibetan Plateau and its surrounding areas. Snowline elevation is related to longitude, latitude, and mountain base elevation (MBE), to construct a multivariate linear regression equation. These three factors could explain 83.5% of snowline elevation's variation in the Tibetan plateau and its surrounding areas. Longitude, latitude, and MBE (representing MEE to some extent) contribute 16.14%, 51.64%, and 32.22%, respectively, to the variability of snowline elevation. North of latitude 32°N, the three factors' contribution amounts to 18.72%, 44.27%, and 37.01%, respectively; to the south, their contribution is 28.12%, 15.37%, and 56.51%, respectively. A non-linear model was also constructed, but it only enhances the ability slightly in fitting of snowline's distribution. Our analysis reveals that latitude and MBE are significant controlling factors of snowline elevation. Longitude, which stands for precipitation to a great extent, has limited impact on snowline's distribution. MEE should be further studied, or directly quantified so that it can be adequately incorporated into the development of spatial models for altitudinal belts, whereby the precision of such models could be greatly enhanced.

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Introduction

Extremely high mountains are often covered with snow throughout the year. The lower limit of the nival zone, where snowfall reaches equilibrium with ablation, is a very important symbolic climate boundary—snowline. It is also taken as the upper limit of alpine belts and one of the symbolic lines of mountain altitudinal belts. Similar to other altitudinal belts, the distribution pattern of snowline is subject to vertical and horizontal zonality. Dissimilar to other altitudinal belts, it is much more sensitive to the effect of temperature, precipitation, and topography.

Wissmann first revealed a concentric pattern of snowline's distribution in the Tibetan Plateau (Hvon, 1959). Li et al. (1986), Shi (1988), and Shi et al. (1992, 2000) made relevant studies afterwards. In the southwest of the plateau, the modern snowline rises up to 6200 m above sea level in the Nganglong Kangri, which is the highest snowline in the northern hemisphere. Snowline declines to about 5000 m in the east. In the big bend of the Yarlung Zangbo in southeastern Xizang (Tibet), snowline is as low as 4500 m (Shi, 1992; Wu, 1989). Quantitative spatial patterns of snowline and some other mountains' altitudinal belts have been explored by relating snowline elevation with its geographical location and considering latitude as a surrogate of temperature and longitude as a surrogate of precipitation (Hermes, 1955; Jiang, 1987, 1993; Körner, 1998; Zhang et al., 2006). Many unitary or dibasic fitting models have been established for snowline or some other altitudinal belts (Hermes, 1955; Jiang, 1993; Körner, 1998; Jiang et al., 2002; Zhang et al., 2006). However, most of these models involve small scales and could not be extrapolated to other regions, while those established for the northern hemisphere or the whole globe are usually of very low precision. For example, the altitude of timber line around equator should be 5068 m if estimated in terms of the model for the Ural mountains (Malyshev, 1993), whereas it is actually about 3500 m in Mt. Kenya and Mt. Kilimanjaro in Africa (Hedberg, 1964). The main reason is that these models could not take into account one of the most important factors controlling the distribution of altitudinal belts—mass elevation effect (MEE).

The concept of MEE was introduced by A. de Quervain in 1904 to account for the observed tendency for temperature-related parameters such as tree line and snowline to occur at higher elevations in the central Alps than on their outer margins (Quervain, 1904; Barry, 1992, 2008). It was first reported in the Alps (Schroeter, 1908). The occurrence of physiognomically and sometimes floristically similar vegetation types at higher altitudes on large mountain masses than on small isolated peaks and even islands are also regarded as MEE in general, and this phenomenon has been discovered and reported for many other regions of the world (Barry, 1992; Flenley, 1995; Leuschner, 1996; Fang and Liu, 1999; Wang et al., 2004; Flenley, 2007). The most prominent example is the lofty Tibetan Plateau, whose thermodynamic effect strongly changes the local climatic conditions and gives rise to greatly different moisture and temperature conditions compared with that in mountains at similar latitudes. At 30°N, the average sea level surface temperature is 18.3 °C, while the temperature converted to sea level from air temperature of Xinjiang at the same latitude reaches 25 °C, which is 6.7 °C higher than the former. In the plateau, the high temperature center locates in the southwestern part of the plateau where the highest modern snowline in the northern hemisphere is found (Shi, 1992).

It is reasonable to suppose that the magnitude of MEE is related to mountain height, mountain base elevation, mountain area, distance to the nearest periphery of high land mass, landform conditions around, etc. It has been shown that the upper limit of the *Fagus* L. forest ascends with the elevation of local ground surface in China (Fang and Liu, 1999); evergreen broad-leaved forest can reach 2500 m in mountains of southwestern China, while only 1000–1200 m in low-lying eastern China (Fang et al., 2004); the highest timber lines on oceanic islands exist on the Hawaiian archipelago, which is the highest oceanic island mountains in the world that rise from extended volcanic masses, demonstrating the influence of mountain height and extension on vegetation zonation (Leuschner, 1996). All of the factors mentioned above can be called MEE factors, and their contribution in determining the magnitude of MEE depends on scale and region. As Flenley (2007) stated, the full explanation of MEE will be a multivariate one, and some factors may be more important in one location, while other factors may dominate elsewhere. In this article we mainly explore the relationship of mountain base elevation with MEE in the Tibetan Plateau and surrounding areas. This plateau is the most massive in the world, and it should create the most powerful MEE.

In spite of the significance of MEE in reshaping local climate and elevating altitudinal belts, we have only perceptual knowledge about it, let alone quantitative research. This paper tries to explore a method for quantifying MEE by considering the contribution of MBE to the altitudinal position of snowline in the Tibetan Plateau and its surrounding areas.

Materials and Methods

STUDY AREAS

The Tibetan Plateau, covering an area of about 2.5×10^6 km^2 with an average elevation of 4500 m above sea level, is the largest and loftiest plateau of the world. There is no doubt that it produces the most prominent MEE and is responsible for the highest timber line (4600 m) of the northern hemisphere in its southeastern part. We collected a total of 143 snowline elevation data for the study area (approximately 26.2–48.44°N, and 73–104.4°E), as shown in Figure 1. They are all from journal articles, books, online documents, and even unpublished works edited by some institutions of the Chinese Academy of Science, as listed in the supporting materials of this paper.

METHODS

Snowline elevation is related to a number of factors, e. g., latitude and longitude (Jiang 1991; Zhang et al., 2006). It should be related to elevation gradient, because snow is usually more difficult to accumulate on steeper slopes. So, snowline elevation should be higher on steeper terrains. However, this occurs on relatively very small scales. On large scales, MEE significantly affects snowline elevation, as stated above. The question is, how can MEE be measured and how much does it, among other factors such as latitude and longitude, contribute to the present altitudinal position of snowline? Here, we use MBE as the representative of MEE to calculate the contribution of MEE to snowline elevation. At first glance, it seems that the higher the mountains or plateaus are, the higher snowline is. But, if we consider things deeply, we find that it is MBE rather than mountain absolute height that matters in creating MEE. The generation of MEE is primarily due to the heating produced by long wave radiation of the mountain surface. Therefore, the higher MBE is, the more heat will be produced, the higher air temperature, and the higher the relevant altitudinal belt. For example, the highly distributed snow and timber lines in the Tibetan Plateau are more likely related to its inner high plateau surface (above 4000 m). In other words, local ground surface elevation or MBE is a significant factor in forming MEE and could be regarded roughly as the size of MEE. To quantify the contribution of longitude, latitude, and MEE to snowline's altitude position, we performed a regression analysis, with snowline elevation as the dependent variable, and longitude, latitude, and MBE as the independent variables. The model is:

$$y = \mathrm{a}x_1 + \mathrm{b}x_2 + \mathrm{c}x_3 + \mathrm{d} \quad (1)$$

where y = altitude of snowline, x_1 = longitude, x_2 = latitude, and x_3 = MBE; a, b, c are coefficients of independent variables, d is a constant term.

We previously found that a quadratic model is a rather good fit to snowline's latitude pattern in China (Zhang et al., 2006). So, we tried to use quadratic forms of the three independents to rebuild the multiple regression equation so as to compare the fitting precision of the two equations. The model is as follows:

$$y = \mathrm{a}x_1^2 + \mathrm{b}x_2^2 + \mathrm{c}x_3^2 + \mathrm{d}. \quad (2)$$

Snowline altitude is quite different in the regions north and south of 32°N (Fig. 2). To the north, it has a typical negative correlation with latitude. But to the south, almost no general patterns take place. Accordingly, we put the data samples into two groups and treated them separately so as to see what happens in the northern and southern areas. A total of 143 data sites are used, of which there are 81 for the region to the north of 32°N, and 62 to the south.

Results and Discussion

Correlation analysis shows that altitude of snowline correlates significantly with latitude and MBE. Longitude has a weak positive correlation with snowline elevation (Table 1). Coefficient of determination (R^2) and *F*-value of analysis of variance

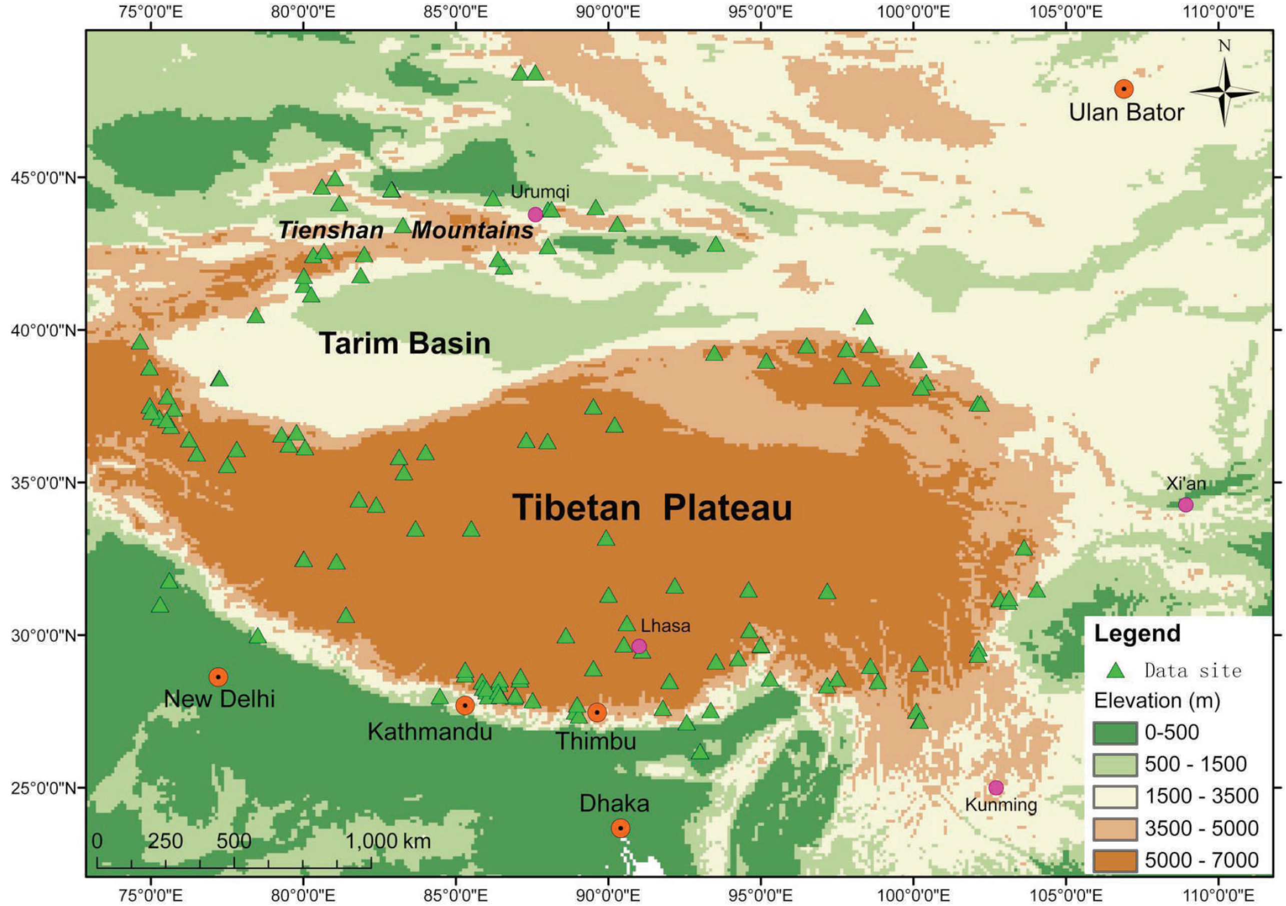

FIGURE 1. Location of 143 snowline data points in the Tibetan Plateau and surrounding areas.

(ANOVA) (Table 2) indicates that the multiple linear regression (MLR) equation could be adequately used to fit the distribution of snowline. *T*-test of regression coefficient demonstrates that the three independent variables have significant correlations with the distribution of snowline. Supposing that the combined effects of latitude, longitude, and MBE to the distribution of snowline is 100%, we can figure out their respective contributing rates based on their Standardized Coefficients (Beta). It can be seen that, for the whole region, latitude contributes the most (51.64%) to the altitudinal distribution of snowline, MBE next (32.22%), and longitude the least (16.14%).

NORTH OF LATITUDE 32N

As Table 3 shows, north of 32°N, the MLR equation fits the distribution of snowline almost perfectly, with a Coefficient of Determination as high as 0.872. *T*-test of regression coefficient indicates that longitude, latitude, and MBE correlate significantly with the distribution of snowline. Latitude is the most important determining factor of snowline elevation (contributing rate is 44.27%), MBE the second (37.01%), and longitude the least (18.72%). The northern areas, far away from the sea, are characterized by continental climate. The effect of solar radiation,

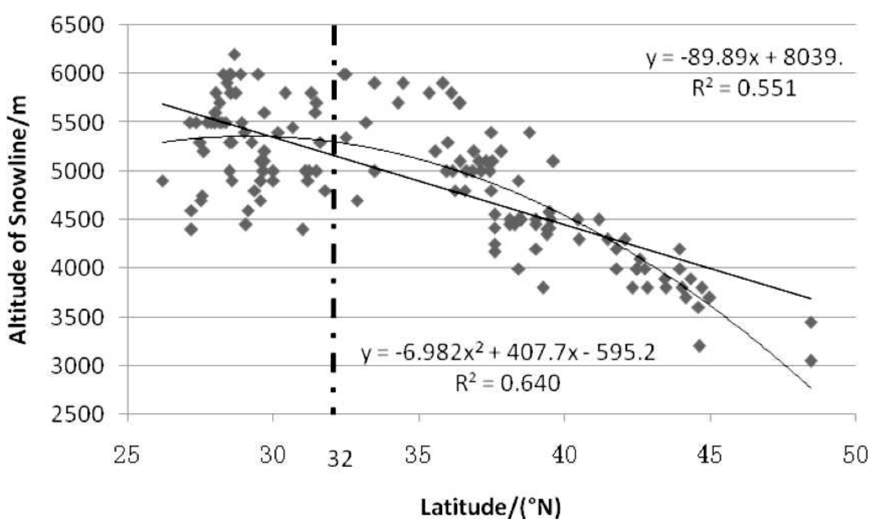

FIGURE 2. Snowline elevation-latitude relations in Tibetan Plateau and surrounding areas.

TABLE 1

The correlations of independent and dependent variables in the model for snowline distribution.

		Longitude	Latitude	Mountain Base Elevation	Altitude of Snowline
Longitude	Pearson Correlation	1	−0.262(**)	−0.146(*)	−0.102
	Sig. (2-tailed)		0.002	0.082	0.223
	Sample number	143	143	143	143
Latitude	Pearson Correlation	−0.262(**)	1	−0.175*	−0.742(**)
	Sig. (2-tailed)	0.002		0.037	0.000
	Sample number	143	143	143	143
Mountain Base Elevation	Pearson Correlation	−0.146	−0.175*	1	0.610(**)
	Sig. (2-tailed)	0.082	0.037		0.000
	Sample number	143	143	143	143
Altitude of Snowline	Pearson Correlation	−0.102	−0.742(**)	0.610(**)	1
	Sig. (2-tailed)	0.223	0.000	0.000	
	Sample number	143	143	143	143

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

TABLE 2

Multiple linear regression model summary, ANOVA, regression coefficients, and their test of significance for the samples in the Tibetan Plateau and surrounding areas.

	Coefficient of Determination (R^2)	F	Unstandardized Coefficients (B)	Standardized Coefficients (Beta)	Contribution Rate (%)	t	Sig.
Constant Term	0.835	234.480 (P = 0.000)	9100.171			25.492	0.000
Longitude			−18.515	−0.226	16.14	−6.195	0.000
Latitude			−87.489	−0.723	51.64	−19.731	0.000
Mountain base elevation			0.211	0.451	32.22	12.624	0.000

TABLE 3

Multiple linear regression model summary, ANOVA, regression coefficients, and their test of significance for samples north of 32°N.

	Coefficient of Determination (R^2)	F	Unstandardized Coefficients (B)	Standardized Coefficients (Beta)	Contribution Rate (%)	t	Sig.
Constant Term	0.879	187.112 (P = 0.000)	9514.427			15.340	0.000
Longitude			−17.730	−0.219	18.72	−5.518	0.000
Latitude			−100.100	−0.518	44.27	−8.145	0.000
Mountain base elevation			0.222	0.433	37.01	6.797	0.000

TABLE 4

Multiple linear regression model summary, ANOVA, regression coefficients, and their test of significance for samples south of 32°N.

	Coefficient of Determination (R^2)	F	Unstandardized Coefficients (B)	Standardized Coefficients (Beta)	Contribution Rate (%)	t	Sig.
Constant Term	0.534	22.176 (P = 0.000)	8315.185			8.446	0.000
Longitude			−19.383	−0.300	28.12	−3.248	0.002
Latitude			−55.292	−0.164	15.37	−1.792	0.078
Mountain base elevation			0.169	0.603	56.51	6.467	0.000

represented by latitude, is relatively high; while the effect of moisture, represented by longitude, is weakened. Consequently, latitude serves as the most dominant factor controlling the elevation of snowline, MBE (represents MEE) is intermediate, and longitude is least.

SOUTH OF LATITUDE 32N

As shown in Table 4, the regression equation does not fit the distribution of snowline very well, for the coefficient of determination (R^2) is only 0.534. In particular, the contributing rates of the three factors change greatly: MBE becomes the leading factor (contribution rate as high as 56.51%), longitude (stands for moist variation) the second (28.12%), and latitude the least (only 15.37%). *T*-test of the regression coefficient shows that latitude has little to do with the distribution of snowline ($p = 0.078$), longitude has a significant negative relationship with snowline elevation ($p = 0.002$), while MBE still is significantly associated with snowline elevation ($p = 0.000$).

This is understandable. Firstly, the southern areas are of enormous topographic relief of thousands of meters, and MBE

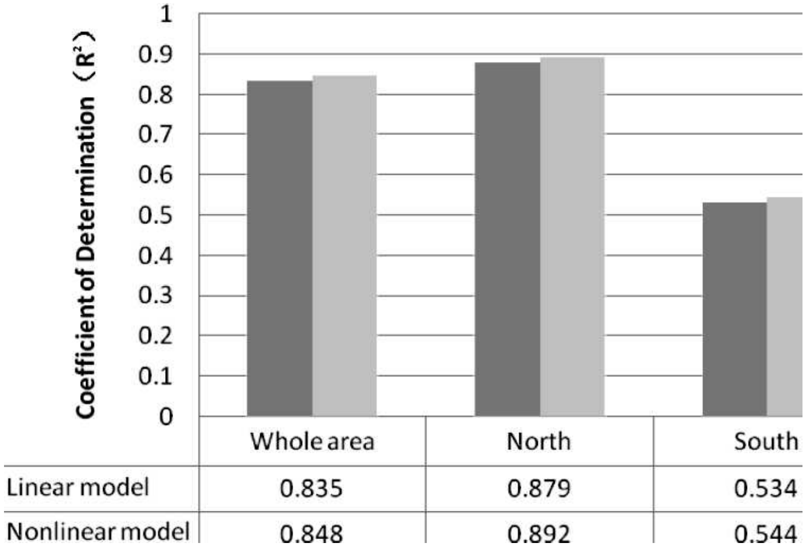

FIGURE 3. Comparison of coefficient of determination (R^2) between linear and non-linear models.

becomes the decisive factor in snowline's vertical distribution of this area. Secondly, the data samples south of 32°N are more concentrated along longitude (only about 5 latitudes) than in the northern areas, so the differentiation of solar radiation represented by latitude is much smaller. Finally, the data samples in the southern areas cover a wide longitude range of about 30°; the eastern parts are close to the sea with a humid climate, and the western data samples are mostly on the plateau with relatively dry or semi-arid climate. Consequently, snowline elevation has a trend of rising from east to west, although this pattern is complicated by enormous topographic relief in the southern areas.

MULTPLE NON-LINEAR REGRESSION MODEL AND RESULT

A non-linear regression model ($y = \mathrm{a}x_1{}^2 + \mathrm{b}x_2{}^2 + \mathrm{c}x_3{}^2 + \mathrm{d}$) can be considered as a linear model with dependent variables' quadratic forms. The computational process is completely the same. Comparing the coefficient of determination (R^2) of the two models (Fig. 3), we found that the fitting precision of the non-linear model is a little higher than the linear model in the whole region and in the northern areas. Another non-linear model with the dependents' mixed form and linear form were also constructed:

$$\left(y = ax_1^2 + bx_2^2 + cx_3^2 + dx_1x_2 + ex_1x_3 + fx_2x_3 + gx_1 + hx_2 + ix_3 + j\right); \qquad (3)$$

the fitting result also is improved very slightly.

Conclusions

(1) The paper tries to quantitatively analyze the contribution of MBE to snowline's distribution based on a linear regression model. Our analysis reveals that latitude and MEE are the two most important factors for the altitudinal distribution of snowline. Longitude, which stands for precipitation to some extent, has relatively limited impact on snowline's distribution. Non-linear models are also developed, and they can improve fitting precision but only slightly.

(2) In different regions with significant topographical or climate changes, the effects of the three impact factors on snowline distribution vary greatly. This means that MEE must be taken into account when developing a distribution model to fit snowline or other altitudinal belts' distribution. Quantitative study of the distribution of snowline or other altitudinal belts should be based on a thorough understanding of their impact factors. Much attention should be paid to the mechanism of snowline's distribution in the future.

(3) MBE can only represent MEE to some extent. Many other factors are also responsible for the magnitude of MEE, including mountain extension, mountain length and trend, distance to the nearest periphery of high land mass, landform conditions around, etc. So, this paper is the first step toward quantifying MEE. In future studies, other factors should be also taken into account, and, if so, MEE could be more effectively quantified.

(4) Quantifying MEE will improve the accuracy and predictive capacity of the fitting models for altitudinal belts. Another factor uplifting or pulling down altitudinal belts is the exposure effect—the elevation of altitudinal belts changes on different slopes due to differences in solar radiation. If MEE and exposure effect could be adequately quantified, it would likely lead to development of a high-accuracy and multi-scale general model for the spatial distribution of altitudinal belts.

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