Mass elevation effect: Concept and quantification

Baiping Zhang
Institute of Geograpahic Sciences
and Natural Resources Research,
Chinese Academy of Sciences
Beijing, China
zhangbp@lreis.ac.cn

Abstract—**Mass elevation effect (massenerhebungseffect, short as MEE in the following) 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. It is a significant factor shaping the three-dimensional pattern of climate, vegetation and soil globally. But in the past, it is mostly neglected in exploring the mechanism of terrestrial complex ecosystems. We have shown that MEE contribute greatly to the actual altitudinal position of snowline and alpine timberline. It should be quantified so as to explain more clearly the geographical and ecological pattern and mechanism of the terrestrial sphere. Two approaches are put forward to quantify MEE, namely indirect and direct quantification.**

I. WHAT IS MEE?

Larger mountain massifs serve as a heating surface absorbing solar radiation and transforming it to long-wave energy. In other words, the climate becomes increasingly continental from the rim to the central parts of the mountain areas, with lower precipitation and higher percentages of sunshine in the inner parts compared to the outer mountain ranges. Consequently, temperature is higher than in the free atmosphere at any given elevation, which makes the identical altitudinal belt at higher position in the interior than in the outer margins of mountain massifs. This is the so-called "Massenerhebungseffect" or "mass elevation effect" [1], sometimes called "Mountain mass effect". This can effectively explain the large difference in elevation of altitudinal belts in similar latitudes. Some extremely high timberlines (in the central Andes and the Tibetan Plateau) are mainly the result of mass elevation effect. Without MEE, the highest timberline should not surpass 3500m above sea level in any mountains. The magnitude of MEE was considered to be closely related with the mean elevation of a mountain massif; however, what is really significant is the base elevation of the local basins or valleys in the inner parts of the massif. To a large extent, the local base elevation could represent MEE, and it has been proved to contribute a lot to the elevation of snowline and timberline [2,3].

By using the concept of MEE, many outstanding geoecological phenomena could be explained more scientifically. For example, the timberline only go upwards to about 3200m in Mt. Kilimanjaro nearly on the equator, only to about 4000m in the southern flank of the Himalayas, while to 4600-4900m in the southeastern Tibetan Plateau. The reason is simple: the mountain base elevation (namely MEE to a large extent) is relatively low (about several hundreds of meters) in Mt. Kilimanjaro and in the southern flank of the Himalayas.

II. HOW MUCH MEE CONTRIBUTES TO THE ALTITUDINAL DISTRIBUTION OF SNOWLINE AND TIMBERLINE？

Snowline elevation is related to longitude, latitude, and mountain base elevation (MBE). According to multivariate linear regression analysis, 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 [2]. If latitude, continentality and MEE are considered the factors determining the elevation of timberline, the coefficient of determination (R^2) of the linear model is as high as 0.904, and the contribution rate of latitude, continentality and MEE to timberline elevation is 45.02% ($p = 0.000$), 6.04% ($p = 0.000$) and 48.94% ($p = 0.000$), respectively. This revealed that MEE is the primary factor in determining the elevation of timberline on continental and hemispherical scale [4]. These researches indicate that MEE has a great contribution to the altitudinal distribution of timberline and snowline. However, the contribution mentioned above is the general relative average on a macro-scale. As a significant factor shaping the ecological and geographical pattern, MEE should be quantified so as to put it into the models explaining the altitudinal distribution of mountain ecosystems [5].

III. QUANTIFICATION OF MEE

The present manuscript intends to use MEE index to represent the magnitude of MEE. We have considered two approaches to realize the quantification of MEE.

1. Indirect quantification. We suppose that the actual altitudinal position of a given altitudinal belt or ecotone (e.g., alpine timberline) is the sum of its ideal elevation and MEE index. If we know the actual

elevation and the ideal position of an altitudinal belt, then we get the MEE index at the given place or mountain slope. So, the key step is to develop an ideal distribution (MEE-free) model for altitudinal belts. It should be such: the altitudinal limits go upwards from high to low latitude, from border to central parts of highland massifs, and from shady to sunny slopes. This way we acquire MEE index from a number of locals. Then, we can expand MEE index to larger areas though appropriate interpolating and extrapolating.

Without MEE, the highest alpine timberline should not surpass 3500m above sea level, no matter in tropical or subtropical regions. This is the ceiling of any ideal models for timberline distribution. This must be taken into account when developing ideal models for global timberline distribution. We also find that warm index, hottest month mean temperature, continentality and annual mean precipitation are the four most significant factors controlling the altitudinal distribution of timberline. They must be considered in developing ideal distribution models of altitudinal belts.

2. Direct quantification. Generally, the magnitude of MEE has been considered to be related with the area, average height, inner base elevation and even the absolute height of a mountain massif. So, if we want to quantify MEE, these geomorphological factors must be involved. Our recent studies have shown that the actual magnitude is closely related with local mountain base elevation (MBE). We have shown in the study of the impact of MEE on timberline altitude that, when the MBE goes upwards of 1000m, the timberline climbs by 600-800m. Of course, MEE may vary greatly from mountain to mountain. The magnitude of MEE may show quite different for two mountains with completely same geometry but in different latitudes, for two massifs with same elevation and different volume, and for two sites at different distance from the border of the same highland [6].

A very important issue is the warmer climate in the inner parts than in the outer parts of highlands [7]. This is the real mechanism of MEE. The quantification of MEE involves the heating effect of inner highland. Fortunately, this effect could be studied with remote sensing data, especially MODIS ground surface temperature data [8], combined with measured data. The final step of quantifying MEE is to explore the relationship between MBE, inner temperature and vertical shift of altitudinal belts (mainly alpine timberline and snowline).

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