Altitudinal Belts: Global Mountains, Patterns and Mechanisms

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Altitudinal Belts: Global Mountains, Patterns and Mechanisms

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Abstract
Climatically sharp altitudinal gradient leads to the diversity and complexity of altitudinal (vegetation) belts and their vertical combinations (spectra) in mountains of the world. A total of 80 altitudinal belts could be identified globally. Almost all altitudinal belts have a trend toward increasing in elevation from high to low latitude, from oceanic to continental climatic regions, from the rim to the interior of immense mountain masses, and from shady slope to sunny slope. Many factors interplay to give rise to their global and local patterns of distribution, among which the most significant geographical factors include latitude, mass elevation effect, and continentality; the most effective ecological factors involve mean temperature of the warmest month, mean temperature of the coldest month, continentality, and annual precipitation.

INTRODUCTION
This entry is to show the diversity and complexity of global altitudinal belts, their basic patterns, and the main mechanisms. The mountains of the world are characterized by numerous and colorful altitudinal vegetation belts and their local-specific combination from mountain base upwards to mountain top (i.e., spectra of altitudinal belts, Fig. 1) thanks to the extremely complex and varied environment on different altitudes and slopes. On one hand, these belts follow a general trend of ascending from polar to tropical regions, from island to continental inland, and from the periphery to central parts of large mountain massifs; on the other hand, local factors (geomorphic, human, and soil factors; and even ocean currents, species competition, beetle infestations, invasive pathogens, and herbivores) could distort the general trend of global-scale distribution and modify the altitudinal limits of these belts to varying degrees. In other words, global and local factors interplay to form the actual distribution of altitudinal belts. Many factors have been used to depict the altitudinal distribution of alpine timberline, for example, warmest-month temperature (10°C), growing season temperature (5.5–7.5°C), soil temperature, etc. But they are often separately or singly used.

It is the integrated effect of these factors that really matters. Our latest study from a geographical perspective shows that, if latitude, mass elevation effect (MEE), and continentality are used as independent factors to linearly model the altitudinal distribution of timberline (N = 516), the coefficient of determination (R²) can be as high as 0.904 for the Northern Hemisphere. This nearly perfectly explains the altitudinal distribution of timberline globally.

Some 14 ecological factors have been thought to relate with altitudinal limits of montane vegetation belts. Our most recent study shows that four factors (mean temperature of the warmest month, mean temperature of the coldest month, continentality, and annual precipitation) could be used to model the global-scale distribution of timberline (R² ≈ 0.94).

GLOBAL ALTITUDINAL BELTS: DIVERSITY AND COMPLEXITY
Environmental gradient is about 1000 times as much in vertical direction as in horizontal, giving rise to the development of distinct altitudinal (vegetation) belts appearing successively with increased elevation in mountains, especially in high mountains. Their types and altitudinal positions are quite different from mountain to mountain and from place to place, thanks to the intricate interaction of zonal, non-zonal, and even human factors causing altitudinal belts. As a result, mountains display extreme heterogeneity and ecological variety, and are characterized by the most diverse landscapes and biological resources in the world. In total, 80 types of altitudinal belts have been identified globally,[1] and their types and altitudinal limits can combine in unlimited ways in different mountains and even on varied slopes, making a kaleidoscopic world of altitudinal belts (Fig. 1).

In the southeastern Himalayas nine altitudinal belts can be identified from piedmont plains to snow-coved peaks, which combine to form an altitudinal spectrum with the largest number of vegetation belts in the world, whereas in the Ural Mountains, only two to three altitudinal belts can be found. The upper timberline can reach up to 4800 m
above sea level in the southeastern Tibetan Plateau and even higher in the central Andes, compared to only about 2000 m or even lower in similar-latitude mountains, especially those on islands. The number, elevation, and combination of altitudinal belts show quite differently in different flanks/slopes in arid/semiarid temperate mountains, but rather moderately in humid tropical and subtropical mountains.

**PATTERNS OF ALTITUDINAL BELTS**

Almost all altitudinal belts have a trend toward increasing in elevation from high to low latitudes, from oceanic to continental climatic regions, from the rim to the interior of immense mountain masses, and from shady slopes to sunny slopes. Especially, the natural high-elevation tree line shows a close association with a physics-driven boundary, the snow line, suggesting a common climatic driver.[2] The upper timberline (forest line) or tree line, as a global phenomenon and the most studied limit of altitudinal belts, is a bioclimatic reference line against which other vertical bioclimatic zones can be defined.

**From High to Low Latitudes**

Typically, snowline and timberline, just as other altitudinal belt limits, ascend from high to low latitudes, but reach their summit at 30° northern latitude and 20° southern latitude, and between these latitudes are relatively low value areas, forming a saddle-shaped global distribution pattern. So, there is no uniform relationship between tree line altitudinal position and latitude. Usually, tree lines decline/ascend steeply between temperate and boreal latitudes but are relatively constant between ~30°N and 20°S. And the pattern is not symmetrical around the equator.[3,4]

**From Coastal to Inland Areas of Continents**

From coastal to inland areas of any continent, the limits of altitudinal belts ascend gradually, usually by 1000–2000 m or even larger. The 2000 m amplitude seen within a narrow latitudinal belt in the temperate zone illustrates that latitude is a very imprecise predictor of tree-line elevation,[2] or the inland position and relief are as significant factors as latitude for the elevation of altitudinal belts. In addition, compared to mountains at similar latitudes in continental areas, tree line on oceanic islands is substantially lower than the continental tree line,[5] and the forest line on the islands is found at 1000–2000 m lower elevations.[6]

**From the Outer Margins to the Interior of Mountain Massifs**

More than 100 years ago, a tendency was observed for temperature-related parameters, such as tree line and snow-line, to occur at higher elevations in the central Alps than...
on their outer margins.[7] This is more evident in the Tibetan Plateau, where the timberline ascends from 3500 m in the southeastern rim to 4700 m in the interior and the snowline from 5000 m to 6200 m. In the European Pyrenees, the timberline is at 1500 m in the rim and 2300–2400 m in the interior. In the comparatively high and dry western cordillera of Bolivia, for example, the upper limit of the occurrences of Polylepis tarapacana (P. tomentella) is about 1000 m higher than the upper limit of P. tarapacana in the humid and lower eastern cordillera.[8] Polylepis climbs even higher, to 5200 m, and even to 5400 m, making the highest tree line in the world.[9]

**Difference between Shady and Sunny Slopes and between Windward and Leeward Slopes**

Usually, a certain type of altitudinal belt appears at a relatively higher position in sunny slopes than in shady slopes. In the Catalina Mts. of Arizona, the fir forest, ponderosa pine forest, oak pine woodland, and dry woodland and Chaparral belts are all at a higher elevation in the south-facing slope than in the north-facing slope.[10] In Mt. Kenya of Africa, the orotropical cloud forest lies between 3100 and 3200 m in the humid south slope and 2650 and 3000 m in the arid north slope.[11] Extremes are not present on the sunny slopes of certain belts (e.g., montane forest), as are present in shady slopes, as in the northern Tien Shan Mountains of northwest arid China. Some east–west extending ranges often serve as significant geographic demarcation (e.g., the Qinling Mts. in central China, as the transition from subtropical to warm-temperate zone), and different spectra of altitudinal belts develop in the southern and northern flanks. On the other hand, altitudinal belts show differently in windward and leeward slopes, often with a higher position in the leeward slope. If the sunny slope is the windward slope at the same time, a complicated situation occurs—the altitudinal belt in question may be at a higher position in the shady slope, depending on the degree of aridity resulting from the interplay of so many climatic factors.

**The Upward Shifting of Altitudinal Belts with Global Warming**

Theoretically, an increase of mean temperature by 6°C would mean an upward shift of timberline by 1200 m.[12] However, the fluctuation of altitudinal belts are related with many other factors (e.g., topography, tree species, etc.), also including the importance of site history to the present timberline dynamics.[13,14] With global warming, some altitudinal belts may disappear. In arid and semiarid areas, the future dynamics of the present montane forest stands at timberline might be controlled by moisture supply rather than by higher temperatures. In addition, fluctuations of climates and timberline were not synchronous and occurred also at different regional and local intensities. In case of a sudden rise of temperature as has been predicted by many models, mountain timberlines would not respond spontaneously, but rather with a time lag of several decades or even centuries. The general trend is being modified by regional, local, and temporal variations and thus is different as to its extent, intensity, and process of change. Consequently, it seems difficult to make generally acceptable statements without restricting them at the same time in view of the many regional and local peculiarities.

**MECHANISM FOR THE ELEVATION OF ALTITUDINAL BELTS**

Many factors together give rise to the great diversity, complexity, and varying elevation of mountain altitudinal belts. Globally, the altitudinal position of all altitudinal belts follows a similar trend to timberline and permanent snow line, suggesting a common physical driver (e.g., temperature). On smaller scales, more factors (topography, microclimate, soil conditions, etc.) participate in the making of altitudinal belts. As a result, altitudinal belts’ heterogeneity increases from the global to the regional, landscape, and local scales. In addition, factors and processes at one scale may not be as important as they are at another scale. Generally, these factors could be classified as geographical, ecological, physiological, and even human interference.

**Geographical Factors**

**Latitude**

In the very early stage of altitudinal belt research, especially on upper timberline, it was noted that the elevation of tree line is closely related with the latitude in which it appears, and many regional tree-line latitude-elevation models were developed. Some authors related the altitude of the climatic timberline to geographical latitude and calculated “timberline gradients.” For example, the gradient between the northern border of Oregon and northern California is 184 m, in the Appalachians 83 m,[15] in the Ural Mountains 71 m, in Middle Siberia 89 m, and in East Siberia 76 m per degree northern latitude.[16] In the southern Andes between 35°S and 55°S, timberline declines south for about 80 m per degree of latitude.[17] It is clear that the empirical gradients are quite different because of the geographical location of the longitudinal (north–south oriented) transects to which they are related.

**Mass elevation effect**

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 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 a higher position in the interior than in the outer margins of mountain massifs. This is the so-called “Massenerhebung effect” or “mass elevation effect,”[27] 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 MEE. Without MEE, the highest timberline should not surpass 3500 m 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.[18,19]

**Continentality**

Gradual ascending of altitudinal belts from coastal to continental inland areas is due to general decreased precipitation and increased degree of continentality in the same direction. In reality, continentality and MEE often combine to shape the spatial pattern of altitudinal belts on a large scale, namely, making it possible for the altitudinal belts to ascend to a very high position, especially in the case of immense plateaus and mountain ranges in the interior of continents. In addition, the forest line on the islands is found between 1000 and 2000 m lower elevations compared to mountains at similar latitudes in immense continental areas,[20] and four factors that are thought to contribute to the forest line depression include: (a) drought on trade-wind exposed island peaks with stable temperature inversions, (b) the absence of well-adapted high-altitude tree species on isolated islands, (c) immaturity of volcanic soils, and (d) an only small mountain mass effect that influences the vertical temperature gradient.

**Slope-facing effect**

Differences in radiation and aridity on different facing slopes may lead to difference in elevation and area of altitudinal belts. The contrast becomes more evident from tropical to temperate zones, and from coastal humid to inland arid areas. But this is only a local driver for altitudinal belts.

Of course, it is the integrated action of these factors that really matters. The latest study shows that, if latitude, MEE, and continentality are used as independent factors to linearly model the altitudinal distribution of timberline (N = 516), the coefficient of determination (R²) can be as high as 0.904 for the northern hemisphere.[20] This nearly perfectly explains the global distribution of alpine timberline.

**Ecological Factors**

Many temperature and aridity factors have been found to closely relate to the elevation of altitudinal belts, including the 10°C isotherm for the warmest-month, mean annual temperature, annual range of temperature, growing-season temperature, soil temperature, aridity, mean annual precipitation, the existence of well-adapted tree-line species, competition between communities or species, etc. In total, 14 ecological factors have been used to separately explain the altitudinal belts. In exploring the “ultimate cause” of altitudinal tree line, it was found that low mean temperatures in the rooting zone during the growing season or all-year-round (at tropical tree lines) is the critical factor controlling directly worldwide tree line position.[21–24] The latest research shows that the current natural high-elevation tree line is associated with a growing season that is at least three months long and during which the mean air temperature reaches at least 6.4°C.[21] With it, in addition to some necessary fine tuning that accounts for regional aridity and snow pack effects, the global pattern of natural climate-driven tree-line positions can be modeled with great confidence. The obtained error term of ±0.7 K corresponds to a mean uncertainty of ±130 m of elevation, sufficiently robust at a global scale to encourage a discussion of the likely causes of the global tree-line isotherm. Our most recent study shows that four factors (mean temperature of the warmest month, mean temperature of coldest month, continentality, and annual precipitation) together could almost perfectly explain the global-scale distribution of timberline (R² ≈ 0.94).

**Physiological Factors**

UV-B (280–315 nm) is damaging and mutagenic to living organisms.[25] It is known to be particularly high in the alpine zone of tropical mountains. This involves the occurrence of dwarf forest at anomalously low altitudes, especially for isolated peaks in tropical mountains. It has also been suggested that temperature could operate via the soil,[26] lower temperatures leading to a greater accumulation of organic matter and to changes in nutrient status. The increasingly poor supply of nitrogen and phosphorus depends on decrease in temperature and the increase in frequency of fog is likely to be important not only in governing the distribution of forest types but also in influencing their biomass and physiognomy. This also leads to relatively lower elevation of forest belts in tropical mountains and islands.

**CONCLUSIONS**

The diversity and complexity of altitudinal belts of the world mountains result from many factors, global and local, zonal and nonzonal, uplifting (e.g., MEE) and depressing (e.g., summit syndrome and wet climate), etc.
As a result, global altitudinal belts have common general patterns and varied local patterns. A difference of 2000–3000 m in elevation of alpine timberline exists both in north–south direction and in similar latitudes. The significance of the traditional latitude-elevation models for altitudinal belts is rather limited. Any single factor, no matter how effective, could not satisfactorily explain the limits of altitudinal belts. On the other hand, it is also not adequate to use too many factors to explain the altitudinal belts, because that means we say nothing about them.

Latitude, MEE, and continentality are the most important geographical factors for altitudinal belts. With them as independent variables, a simple regression equation could almost perfectly explain the elevation of altitudinal belts on global scale. From ecological perspective, mean temperature of the warmest month, mean temperature of the coldest month, continentality (also an ecological factor), and annual precipitation are four most significant factors, which together could also rather satisfactorily explain the global distribution of altitudinal belts.

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