Integration of Data on Chinese Mountains into a Digital Altitudinal Belt System

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Diverse mountain environments in China

With about 70% of its land area comprised of mountains and plateaus, China is the most extensive mountainous country in the world (Zhang et al 2004). From south to north, it extends for about 5500 km, with an accumulated temperature ranging from about 9000°C to less than 1700°C for the period of daily mean temperature ≥10°C (Huang 1959). Climatically it includes almost all temperature zones from equatorial and tropical to cold temperate. From east to west, it covers a distance of 5200 km, with annual mean precipitation decreasing from 800–1500 mm to about 50 mm (Zhao 1986). Accordingly, various landscapes—humid forest, semi-arid grassland, and arid desert—have developed from southeast to northwest, as distance from the Pacific Ocean increases.

The high degree of diversity in climate and landscape is greatly augmented by the existence of many well-known giant mountain ranges such as the Himalayas, the Karakoram, Kunlun, Hengduan, Tian-shan, Qinling, Helan, and Yinshan mountains. Most of these serve as significant climatic boundaries. For example, in northwest China, the Tianshan divides Xinjiang into warm-temperate southern and temperate northern zones; the Qinling in east China demarcates subtropical and warm-temperate zones; the Yinshan forms the dividing line between temperate and warm-temperate; and the Helan demarcates the arid and semi-arid regions in northwest China. These ranges complicate the patterns of climate and landscape in the country.

China’s environment is further diversified by the existence of the world’s most immense and youngest plateau, the 2,500,000-km² Tibetan Plateau, with an average altitude above 4500 m. Well known as “the roof of the world,” it towers to the middle of the troposphere as a “hot island” and generates so-called “Tibetan atmospheric circulation” and the “Tibetan Monsoon System;” ie wind blows outward in winter and inward in summer (Gao and Ye 1984).

The most significant effect of the Plateau as a “hot island” is the inducement and reinforcement of the so-called “Southwestern Monsoon” from the Bay of Bengal. Thanks to this effect, subtropical monsoon climate extends northward to the southern piedmont plains of the Himalaya, and even to northern latitude 29°30′, or the Great Bend of the Yarlungzangbu River, nearly 6° north of the Tropic of Cancer. Climatically this forms the so-called “hot tongue” in the southeastern Plateau. Other parts of the Plateau, especially the west and the north, receive little moisture-laden air masses either from the Bay of Bengal or from the Arabian Sea. As a result, the annual mean precipitation decreases from more than 4000 mm in the southern flank of the Himalaya to only about 20–50 mm in the northern flank of the Kunlun and in the Qaidam Basin. Precipitation decreases enormously from about 800–1000 mm in the east to about 50 mm on the high western plateau (Liao 1990).

Between northern latitudes 35°00′–36°30′ and eastern longitudes 83°–86° there is a very dry region without flowering plants and almost only bare land. This is the “high-cold arid core of the Tibetan Plateau” (Zheng 2000). This pattern of regional climate, together with the striking vertical differentiation in its peripheral high and extremely high mountains, gives rise to varied climate types on the Plateau, from humid subtropical monsoon in the southeastern corner to extremely arid and frigid/cold climate in the northwest and in the extremely high, snow-covered mountains. This results in a great variety of ecosystems and ecological processes on the Plateau (Li 1994) and even the development of...
some special types of ecosystems endemic to China, such as the alpine steppe and alpine desert (Zhang et al. 2002). Chinese botanists and physical geographers have investigated and classified altitudinal belts in the country (Hou 1963; Liu 1981; Zhang 1994; Peng and Chen 1999; Zheng 2000; Zhang et al. 2003) since the late 1950s.

In short, the vast, mountainous characteristics and the dynamic and thermal effects of the Tibetan Plateau give rise to diverse climate types in China, which in turn result in diverse horizontal physical zones and altitudinal belts in the country. The complexity and diversity of altitudinal belt distribution in China leads to great diversity of landscapes—an important aspect of global biological diversity. Drawing on a review of biogeographical literature and abundant field results presented over the past 10 years, the present article demonstrates and broadly categorizes altitudinal belts, their digital integration, and the basic spatial patterns of major belt limits. The method succinctly presented here for integrating China’s altitudinal belts into a digital system could be used for integration of altitudinal belts worldwide into a GIS for demonstration and scientific analysis. This could greatly facilitate both mountain research and mountain management. It can also facilitate digital analysis of the spatial patterns of any given altitudinal belt.

**Diversiform mountain altitudinal belts**

High mountains are usually characterized by different vegetation types at different elevations, mainly owing to varying climatic conditions as altitude increases. These altitudinal belts are combined in various vertical "spectra." For example, a total of 9 altitudinal belts were identified on Mt Namjagbarwa (7782 m) at the eastern end of the Himalaya (Peng 1986), while there were only 3 altitudinal belts in mountains of a comparable size on the northern Tibetan Plateau (Zhang 1995). Moreover, the same types of altitudinal belts can have very different elevations and vertical ranges in different mountains, mountain sections, or even flanks. The structure of a spectrum, including its base belt type (ie the belt constituting the base of a mountain), the number and vertical range of belts, the dominant belt type (ie the belt or belts with the greatest extent in the spectrum), and possibly a characteristic belt (ie a belt whose occurrence is unexpected and/or characteristic of the region), is the result of interaction among horizontal and vertical differentiating factors, and constitutes the scientific basis for environmental management in mountains (Uhlig 1995; Zhang et al. 2003).

According to the prevailing definition in China since the late 1950s, an altitudinal belt is characterized by the same type of plant formation and soil group. It corresponds to a horizontal physico-geographical zone. In the past 50 years Chinese geographers and botanists have identified a total of 63 altitudinal belts, 31 of which can be called "base belts," as they correspond to the basic climatic regimes at the base of mountains in the country (Table 1; Huang 1959; Zheng 1979). The other 32 altitudinal belts occur in various combinations above the base belts, constituting "spectra" that characterize specific locations throughout the country (Table 2; Zhang et al. 2003; Zhang et al. 2005).

Altitudinal belts take on various forms from area to area. A rather general pattern might be as follows: the number of altitudinal belts in a spectrum decreases from southern China to northern China and from the east to the west, and the limits of the same types of belt decrease from south to north but increase from east to west (Liu 1981). Against this background, many secondary patterns have been identified on smaller scales. At least 6 main spatial patterns can be identified in mountain regions of China.

**Monostructural pattern**

All spectra have the same number of altitudinal belts and an identical vertical combination. Differences lie only in the elevation and vertical range of the same belt. This can be seen in the northern Tianshan mountains (Figure 1). A similar environment is found in the 1800-km-long northern flank of the Tianshan range in China. Of course, the vertical range and elevation of the same belt type can vary from one spectrum to another.

**Flattening structure pattern**

The northern flank of the Kunlun range on the northern periphery of the Tibetan Plateau is an example of this pattern (Figure 2). From west to east, the number of altitudinal belts in the spectra decreases (Zhang 1995), ie the structure of the spectrum becomes simpler from west to east, with the forest-steppe belt and alpine meadow gradually disappearing and the breadth of the other belts gradually increasing. This spectrum pattern confirms the climatic pattern of increasing aridity as one moves eastwards in West Kunlun (Zheng and Zhang 1989; Zhang 1995).

**Exposure-dependent pattern**

Altitudinal belt spectra can be constituted quite differently on different exposures of the same mountain. Mt Daqing in Inner Mongolia can be taken as an example. Four spectra in 4 directions have the same base belt, but the upper limit of the base belt is higher on sunny slopes than on shady ones. Moreover, the middle part of the 4 spectra are montane steppe on sunny slopes, montane evergreen coniferous forest in semi-sunny for-
est, and deciduous and broad-leaved mixed forest on shady and semi-shady slopes. The upper parts of the 4 spectra differ enormously: sub-alpine shrub-meadow on sunny slopes, montane shrub-meadow on semi-sunny slopes, montane dwarf forest on semi-shady slopes, and deciduous/needle-leaf forest on shady slopes. This can be briefly explained as follows: in the mid-latitudes, slopes with different exposures receive quite different amounts of sun radiation, so they have distinct temperature and humidity regimes and develop various altitudinal belt spectra.

### Stepwise-rising pattern

In the peripheral areas of the Tibetan Plateau, some altitudinal belts rise step by step instead of gradually from outside areas to the inner valleys of high mountains or to the inner side of the Plateau. An example is the stepwise jumping of montane desert belts from 2000–3000 m on the northern flank to 3000–5000 m in the heartland of the Kunlun mountains (Zhang 1995).

### Abnormal pattern

Some abnormal altitudinal belt spectra were found.
### Table 2

Altitudinal belts (excluding the base belts listed in Table 1) that occur in various combinations constituting spectra with regional characteristics. (Sources: literature survey and field work)

<table>
<thead>
<tr>
<th>Altitudinal belt group</th>
<th>Altitudinal belts (excluding base belts)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alpine group</strong></td>
<td>Nival belt, Subnival belt, Alpine meadow, Alpine steppe-meadow, Alpine steppe, Alpine desert-steppe, Alpine desert</td>
</tr>
<tr>
<td><strong>Sub-alpine group</strong></td>
<td>Sub-alpine meadow, Sub-alpine shrub-meadow, Sub-alpine shrub, Sub-alpine evergreen coniferous shrub, Sub-alpine krummholz, Sub-alpine coniferous forest</td>
</tr>
<tr>
<td><strong>Middle and low mountain group</strong></td>
<td>Montane coppice forest, Montane shrub-meadow, Montane evergreen coniferous forest, Montane deciduous coniferous forest, Montane broad-leaved and coniferous mixed forest, Montane deciduous broad-leaved and coniferous mixed forest, Montane deciduous broad-leaved mixed forest, Montane forest-steppe, Montane shrub-steppe, Montane steppe, Montane desert-steppe, Montane desert shrub-steppe, Montane steppe-desert, Montane desert, Montane evergreen deciduous broad-leaved mixed forest, Montane seasonal-green broad-leaved forest, Montane evergreen broad-leaved forest, Montane monsoon rainforest</td>
</tr>
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One was the development of quasi-savanna (shrub-steppe) belts under evergreen broad-leaved forest in some areas of the southeastern Tibetan Plateau. This is closely related to the special geoeccological phenomenon of so-called “dry-hot valleys” (Zheng 2000).

**Tibetan complex pattern**

A special vegetation pattern has evolved on the Tibetan Plateau due to its immensity and to the dynamic and thermal effects stated above. From southeast to northwest, montane forest/shrub, alpine meadow, alpine steppe and alpine desert zones appear in succession. This pattern is referred to as “plateau zonation of vegetation” (Chang 1981) and “Tibetan zonation of vegetation” (Zhang et al 2002). On each of the Plateau zones, different spectra develop, with these zones as base belts. This constitutes the Tibetan complex pattern of spectrum distribution.

**Digital integration and analysis of altitudinal belts**

Traditionally, altitudinal belts and their vertical spectra are drawn by hand on paper. Once this is done, it is difficult to change their colors and position. It is even more difficult to look up the altitudinal belts of any...
region and to analyze their spatial patterns and relationship with the environment. Traditional GIS software (eg Arc/info, even ArcGIS) is known to only deal with plane elements such as points, lines and area, but cannot cope satisfactorily with vertical elements. In other words, traditional geographical and GIS methods were found to be insufficient to integrate various altitudinal belts.

Recently, the authors developed a data model or “digital engine” for altitudinal belts. The model has made it possible to digitally integrate altitudinal belt data throughout China and connect these data with GIS functions, using ArcGIS 8.3 software and VB programming language (Balena 1999; ESRI 2001a, 2001b, 2001c, 2001d; Zeiler 2001; Zhang et al 2005). The basic steps used to construct the altitudinal belt GIS were:

1. Entering altitudinal belt data in a specific data table (.xls), saved as tabular data;
2. Transforming tabular data into vector data (.shp) in ArcGIS;
3. Accessing vector data and acquiring attribute values;
4. Saving attribute values as two-dimensional arrays serving as a data source of graph control (MSChart);
5. Visualizing altitudinal belts and formulating queries about geographical location and vertical distribution of altitudinal belts.

The resulting GIS user interface is now available at the State Key Lab for Resources and Environment Information System, Chinese Academy of Sciences. It digitally integrates belt data for 63 altitudinal belts and 239 spectra, and makes it possible to investigate the positioning, quantification and visualization of altitudinal belts. It includes almost all mountains in China.

With this GIS, it is quite easy to show altitudinal belts digitally for any region, and to query both the geographical and the vertical distribution of a given belt (Figure 3). This can greatly facilitate simple or multiple correlation analysis of spatial patterns of altitudinal belts and their relations to environmental factors. This GIS also has a data export function, making it possible to conveniently export data selected from this system to other software (eg SPSS or Matlab) to carry out data analysis. The following spatial analysis of snowline and forest line in China is an extension of this GIS.

Analysis of spatial pattern of snowline in China
Snowline, as the balance line of accumulation and thaw of snow on high mountains, is a sensitive indicator of regional climate and climate change. It is also closely associated with ice and water resources in high mountain regions. Of the 239 altitudinal belt spectra contained in the mountain GIS, a total of 103 had snowline. Exporting data on altitude, latitude, and longitude to SPSS software and conducting a correlation analysis produced the following result: the height of the snow-
line (H) was closely related to latitude (x), as shown in Figure 4.

The linear equation indicates that the snowline drops by 97 m per degree of latitude when moving northwards in China. The quadratic model has the highest $R^2$ value, up to 0.76, even higher than the cubic and other statistical models. In other words, the quadratic model can best describe the latitudinal pattern of snowline in China. At about northern latitude 32°, the snowline reaches its highest position, i.e., on the northern flank of the Himalaya.

The longitudinal snowline pattern can be exemplified by the Tibetan Plateau. Analysis shows that linear equations did not offer a satisfactory description of longitudinal snowline variation, with an $R^2$ value of only 0.1. The quadratic model is rather good, for its $R^2$ amounts to 0.43, or $R=0.66$. This means that both latitudinal and longitudinal distribution patterns of snowline can be modeled with quadratic equations, with differences only in coefficient.

**Analysis of spatial patterns of forest line in China**

As is well known, forest line is also one of the most sensitive indicators of climate change. Our mountain GIS contains 108 altitudinal belt spectra with forest line. Our analysis shows that both linear and quadratic models fit the latitudinal pattern of forest line (Figure 5), with $R^2$ values of 0.610 and 0.612, respectively. But the longitudinal distribution pattern only fits with quadratic and cubic models (Figure 6; y stands for longitude), while other statistical models have very low $R^2$ values.

It appears that the quadratic model can digitally establish the relation between the height and the latitude or longitude of any altitudinal belt—the only exception we have found so far is the longitudinal distribution of alpine meadow. Its height seems to have no statistical relation to the longitude of its distribution. This hypothesis certainly needs to be tested with more data and further analysis.

**Discussion and conclusions**

The present manuscript has presented a systematized digital collation of altitudinal belt data across China and attempted to demonstrate in an exemplary manner the diversity of these data based on a GIS-supported analysis. It recognizes that the structure of altitudinal belt spectra is also affected by human activities. The lower or upper limits of some belts have undergone ver-
tactical shifts due to human intervention. For example, field work and interviews with local people revealed that the lower limit of the montane coniferous forest belt has moved upwards by about 100 m from 1500 to 1600 m on the northern flank of the Tianshan Mountains due to logging since 1958, and the whole altitudinal spectrum is thus classified as “distorted vertical spectrum.” A second case is the complete change in the base belt that occurs in the mountains of northern China (Peng and Chen 1999; Zhang et al 2003): namely, deciduous broad-leaved forest is replaced by shrub-steppe. This is classified as a “secondary vertical spectrum” (Zhang et al 2003). Transformation of vertical spectra due to human disturbance (mainly deforestation and overgrazing) should be further studied for a full understanding of variations in altitudinal belts and their spectra. Moreover, the evolution of some belts, sensitive to environmental change, can be connected to global change (Jian Ni 2000).

The present article deals only with diversity and basic spatial patterns of vertical spectra, without going into ecological and climatic explanations. This does not mean that such explanations are insignificant; on the contrary, they are very important and should be carefully elaborated.

Although the study of altitudinal belts in China has progressed in the past 50 years, data accuracy is still a problem. Almost all the data are precise only within 100 meters. There are only very limited data for some mountains—not enough to demonstrate vertical vegetation zonation. For some mountains there are virtually no data. Consequently, digital altitudinal belt identification techniques using high-resolution remote-sensing data and digital elevation models should be developed for data collection in mountain regions with a data gap.

The development of the altitudinal belt GIS presented in this paper enables the visualization of altitudinal belts and provides a powerful tool for analysis of any belt in any region in China. But this system currently only covers the main types of altitudinal belt spectra. Further efforts are needed to include more data on subtypes. The digital model of altitudinal belts could potentially be used to integrate mountain data worldwide and help standardize the understanding of altitudinal belts and their relation to various environmental factors.

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