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

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China has a great variety of altitudinal belts due to its size, its numerous high mountains, and the dynamic and thermal effects of the immense Tibetan Plateau. 63 altitudinal belts—31 of which can be called "base belts" as they correspond to the basic climatic regimes at the foot of mountains—have been identified, and a standardized and hierarchized classification for the climatic regimes is outlined. The other 32 altitudinal belts occur in various combinations above the base belts, constituting "spectra" that characterize specific mountain locations throughout the country. Spatial patterns of altitudinal belts are generalized into 6 patterns: the monostructural, flattening structure, exposure-dependent, stepwise-rising, abnormal, and Tibetan complex patterns. Traditional GIS techniques have difficulties dealing with altitudinal belts and their vertical combination or spectra. To tackle this complexity, a data model for altitudinal belts and their spectra was devised. Using ArcGIS 8.3 software, the authors also developed a GIS user interface that makes it possible to digitally integrate, position and visualize altitudinal belts and their spectra throughout China. A total of 239 spectra have been collated to date. This user interface makes it possible to rapidly query the geographical and vertical distribution of altitudinal belts, climatic regimes and spectra in any region of China. It thus provides a solid basis for further analysis of altitudinal belts and their relationship with environmental factors, and could be a key technical basis for integrating and systematizing altitudinal belts worldwide.

Keywords: *Altitudinal belts; altitudinal spectra; climatic regimes; landscape diversity; digital data integration; China.*

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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, Tianshan, 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-km^2 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 "wet 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 results 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-

TABLE 1 Hierarchized classification of climatic regimes (corresponding to altitudinal base belts) in China. (Sources for climatic regimes: Huang 1959 and Zheng 1979)

Natural realms	Temperature zones	Climatic regimes ("base belts")
East monsoon realm	Cold-temperate	1. Deciduous/needle-leaf forest
	Temperate	2. Needle-leaf/deciduous broad-leaved mixed forest 3. Forest-steppe 4. Temperate steppe
	Warm-temperate	5. Deciduous broad-leaved mixed forest 6. Deciduous broad-leaved forest 7. Deciduous broad-leaved forest and forest-steppe 8. Warm-temperate steppe
	Subtropical	9. North subtropical deciduous broad-leaved forest and evergreen broad-leaved mixed forest 10. Mid-subtropical evergreen broad-leaved forest 11. South subtropical evergreen broad-leaved forest 12. Tropical evergreen broad-leaved forest
	Tropical	13. Tropical seasonal rainforest (east) 14. Tropical seasonal rainforest (west)
	Equatorial	15. Equatorial rainforest
Northwest arid realm	Temperate	16. Typical steppe 17. Dry steppe 18. Desert-steppe/brown desert soil (east) 19. Desert-steppe/gray desert soil (east) 20. Desert/gray desert brown desert soil 21. Desert-steppe/brown desert soil (west) 22. Desert-steppe/gray desert soil (west)
	Warm-temperate	23. Desert/brown desert soil
Cold Tibetan realm	Moderately warm	24. Montane needle-leaf forest 25. Shrub steppe
	Cool-warm	26. Montane steppe and needle-leaf forest 27. Montane semi-desert and desert 28. Montane desert
	Cold	29. Alpine shrub-meadow 30. Alpine steppe
	Freezing	31. Alpine desert or semi-desert

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)

Altitudinal belt group	Altitudinal belts (excluding base belts)
Alpine group	Nival belt
	Subnival belt
	Alpine meadow
	Alpine steppe-meadow
	Alpine steppe
	Alpine desert-steppe
	Alpine desert
Sub-alpine group	Evergreen shrub-meadow
	Sub-alpine meadow
	Sub-alpine shrub-meadow
	Sub-alpine shrub
	Sub-alpine evergreen coniferous shrub
	Sub-alpine krummholz
	Sub-alpine coniferous forest
Middle and low mountain group	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

FIGURE 1 Altitudinal belt spectra in the northern Tianshan mountains, showing 11 spectra on the northern flank. Montane desert is the base belt for all spectra. The dominant belt or belts in each case are the belts with the maximum vertical range in a spectrum (not including the subnival and nival belts), eg for Mt Tomor, montane desert is also the dominant belt, while for Mt Borohoro, montane desert and alpine meadow are the dominant belts.

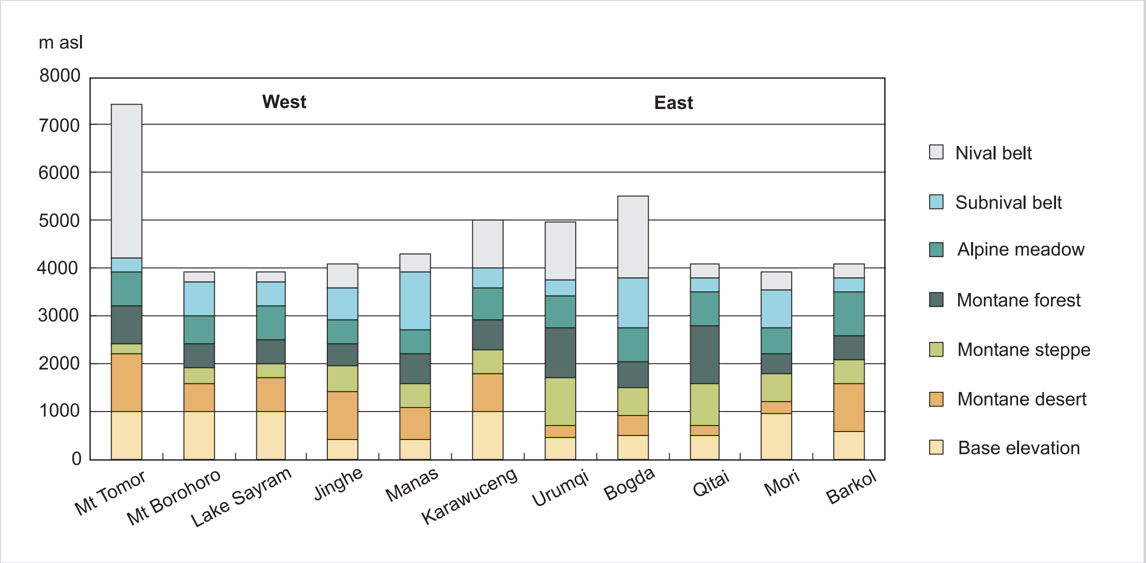
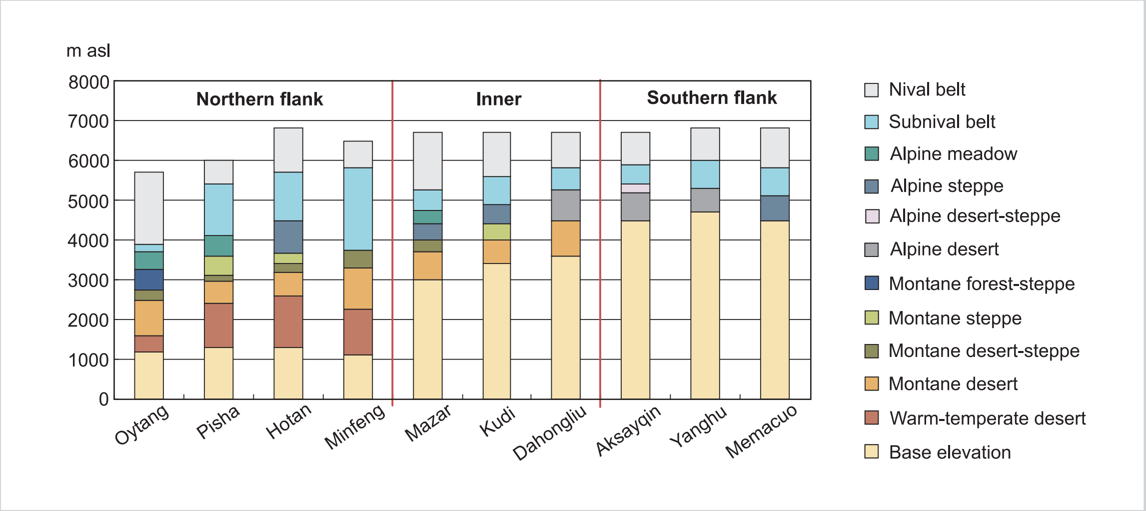


FIGURE 2 Altitudinal spectra in the Kunlun mountains (source: Zhang 1995, p 288). Here the base belt of the Oytag spectrum is warm temperate desert, and that of Memacuo is alpine steppe. The Oytag spectrum has a very special belt—its characteristic belt: the montane forest-steppe belt, which does not appear in other spectra of the Kunlun mountains.



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 geoecological phenomenon of so-called "dry-hot valleys" (Zheng 2000).

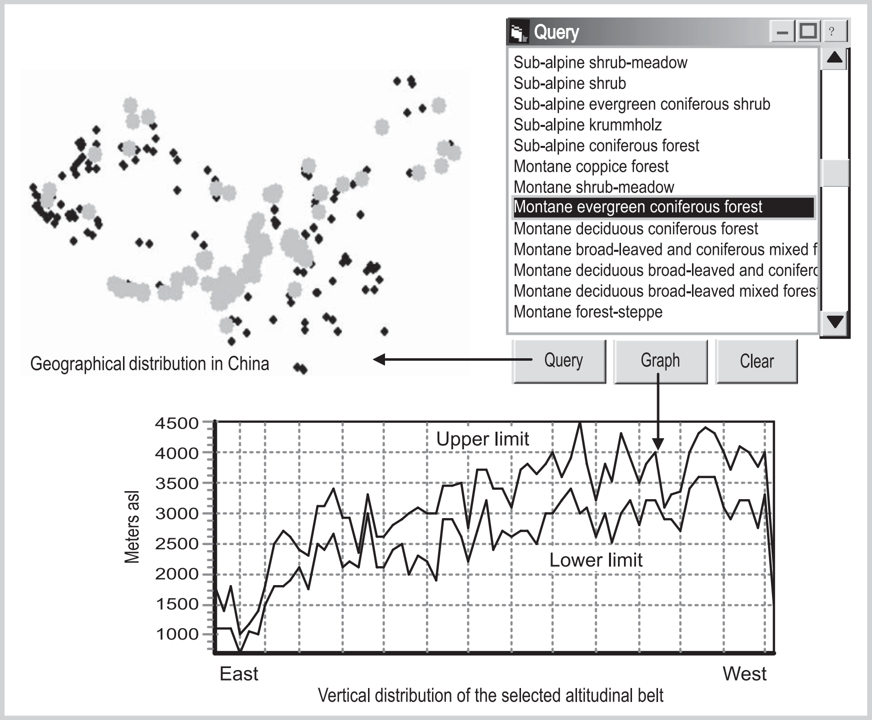
Tibetan complex pattern

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

FIGURE 3 Example of the geographical and vertical distribution of a given altitudinal belt using the authors' "digital engine." The graph shows the vertical distribution of the selected altitudinal belt from the east (left) to the west (right) of China.



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-

FIGURE 4 Latitudinal pattern and digital fit of snowline in China. (Source of data: GIS-based data model presented in this paper)

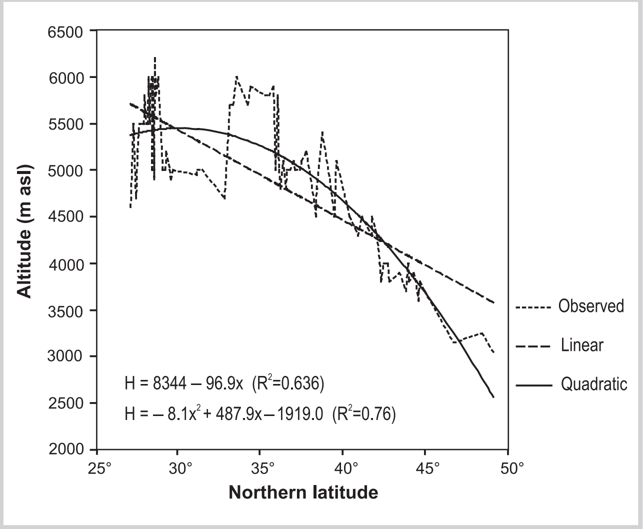
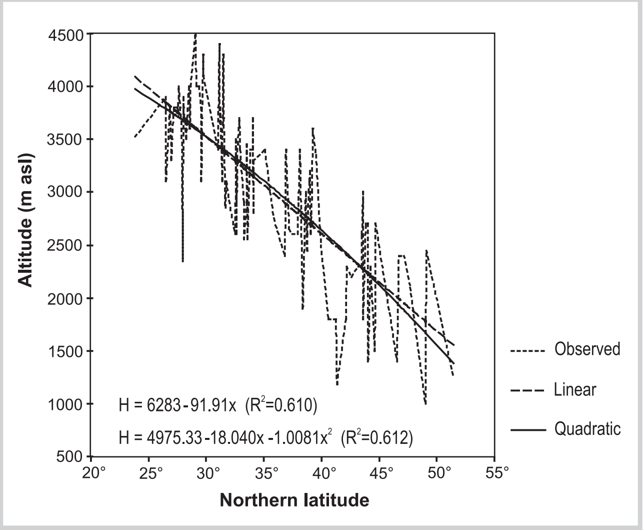


FIGURE 5 Latitudinal distribution pattern of forest line in China. (Source of data: GIS-based data model presented in this paper)



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, ie 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

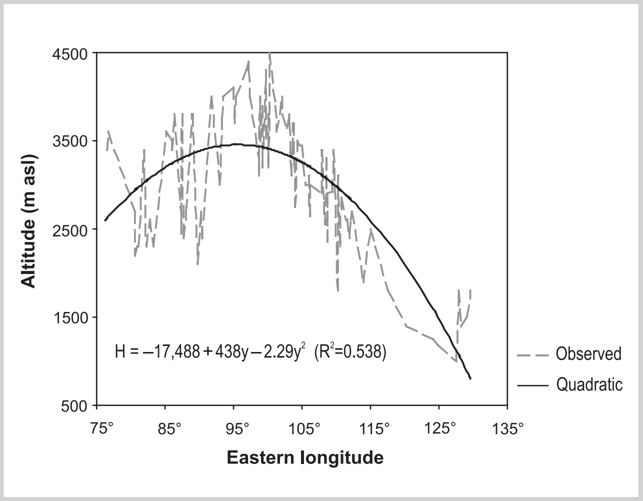
As is well known, forest line is also one of the most sensitive indicators of climate change. Our mountain GIS contains 108 altitudinal belt spectra with forest line. Our analysis shows that both linear and quadratic models fit the latitudinal pattern of forest line (Figure 5), with R^2 values of 0.610 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-

FIGURE 6 Longitudinal pattern of forest line in China. (Source of data: GIS-based data model presented in this paper)



tical 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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