Available online at www.sciencedirect.com
ScienceDirect

Agricultural and Forest Meteorology 139 (2006) 200–207

AGRICULTURAL AND FOREST METEOROLOGY

www.elsevier.com/locate/agrformet

Temperature variation along the northern and southern slopes of Mt. Taibai, China

Zhiyao Tang *, Jingyun Fang

Department of Ecology, College of Environmental Science, Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China

Received 16 May 2005; received in revised form 3 July 2006; accepted 3 July 2006

Abstract

Altitudinal change in temperatures has a major effect on the distribution of plants and vegetation along an elevational gradient in mountainous areas. In order to explore changes in temperatures in Mt. Taibai (3767 m a.s.l.), Qinling Mountains, the highest mountain in eastern mainland China, we used temperature microloggers to measure the temperature throughout a year on the northern and southern slopes. The measurement was conducted at 16 different elevations between 1250 and 3250 m from August 2001 to July 2002. The results showed that with an increase of altitude, the annual mean temperature (AMT) decreased at a lapse rate of 0.34 ± 0.04 and 0.50 ± 0.02 °C/100 m on the southern and northern slopes, respectively. The lapse rates of monthly mean temperatures (MMT) showed a large seasonal difference, with a higher value in the summer than in the winter, ranging from 0.14 ± 0.05 to 0.43 ± 0.05 °C/100 m on the southern slope, and from 0.29 ± 0.03 to 0.63 ± 0.02 °C/100 m on the northern slope. The accumulated temperature above 0 °C (AT0) decreased at a lapse rate of 98.6 ± 13.0 and 142.5 ± 3.75 °C days/100 m along the southern and northern slopes, respectively. The annual mean diurnal range of temperature (ADRT) was higher on the southern slope than on the northern slope, while the annual range of temperature (ART) showed a converse pattern. The ART declined at a lapse rate of 0.24 ± 0.07 and 0.32 ± 0.04 °C/100 m on the southern and northern slopes. Our results revealed that lapse rates of temperature variables showed large spatial and seasonal changes, and these changes should be taken into account for analysis of vegetation–climate relationships in mountainous areas.

Keywords: Altitudinal lapse rate; Annual range of temperature; Diurnal range of temperature; HOBO micrologger

---

1. Introduction

A large part of the earth's surface is mountainous, and mountains are integral and important parts of the climate system (Beniston et al., 1997). Climatic factors such as temperature, precipitation, solar radiation, and air moisture show large spatial variations in mountainous areas (Barry, 1992). The microclimatology of montane landscapes is dependent on latitude, continentality and topography. Although the effect of elevation on climate has been long recognized, long-term and systematic *in situ* measurements are very limited in mountainous areas (Richardson et al., 2004). Climate stations are especially sparse at mid and high elevations and remote areas due mainly to the difficulty of installing and maintaining meteorological instruments, and it is therefore difficult to obtain precise climatic data in mountainous areas (Friedland et al., 2003; Beniston et al., 1997). Researchers interested in

---

* Corresponding author. Tel.: +86 10 6276 5578; fax: +86 10 6275 6560.

E-mail address: zytang@urban.pku.edu.cn (Z. Tang).

0168-1923/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2006.07.001

these areas are often forced to extrapolate from data collected in nearby low-elevation sites. Obtaining precise meteorological records in these areas has required major effort (e.g., Hasenauer et al., 2003; Xia et al., 1999; Bolstad et al., 1998; Nullet et al., 1995; Juvik et al., 1993). This is certainly true in the high mountains of temperate China. For example, in China we know little about the temporal variation (at either the diurnal or seasonal scale) in the lapse rate of air temperature, and little data has been published. In order to better understand the links between climate and vegetation, more climatic data from along the elevational gradient is needed. The only viable approach for fully and accurately characterizing the climate in these environments is the collection of real data through field instrumentation. Newly developed equipment, the HOBO micrologger (HOBO H8 Pro, Onset Computer Corporation, Cape Cod, MA, USA; with a measuring range of −30 to +50 °C and a resolution of 0.2 °C), fulfils this purpose. It provides an inexpensive and convenient approach for collecting climatic data in remote areas, especially for analysing fine scale relationships between microclimate and topography. Although good descriptions and accurate measurements of microclimates in mountainous areas have been made, they either covered only a short measurement period (Lookingbill and Urban, 2003) or covered a narrow elevational range (Körner and Paulsen, 2004; Richardson et al., 2004). This means that long-term mean values and seasonal variations of the climatic conditions in mountainous areas have not been available. Here, we present a study of a mountain climate run for more than 1 year and across an elevational range of more than 2000 m along the northern and southern slopes of Mt. Taibai, Qinling Mountains, the highest mountain and the most critical boundary for climatic and vegetation distribution in eastern mainland China due to its west-to-east alignment. The purpose of our study is to explore altitudinal and seasonal variations in temperatures, and to compare their variation on different slopes.

2. Study area and data analysis

2.1. Study area

The Qinling Mountains (32°30′N–34°45′N and 104°30′E–112°45′E) constitute a huge physical obstacle for north- and southward movement of air masses due to their high elevation and east to west arrangement and are thus critical to the distribution of climate and life zones in eastern part of China. The peak, Mt. Taibai (107°45′E, 33°57′N, 3767 m a.s.l.), is the highest mountain in the eastern mainland China, and one of few mountains high enough to extend above the timberline

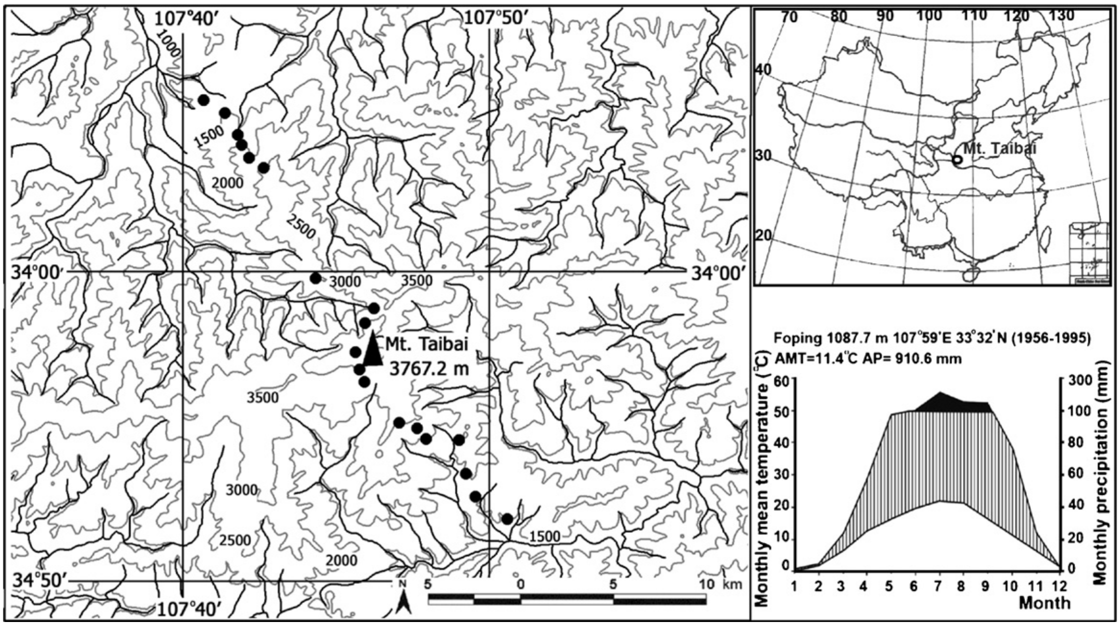

Fig. 1. Study area map illustrating recording sites on the southern and northern slopes in Mt. Taibai, Qinling Mountains. The contour interval on the topographic map is 500 m. The schematic map of China shows the location of the study area in China, and the ecological climate diagram illustrates the climate characteristic of a nearby station, Foping station, which is about 40 km south of the study area. The dark area in the diagram indicates the period in the year when the precipitation exceeds 100 mm per month in the Qinling Mountains.

in eastern part of China (Wang et al., 2004). The climate of Qinling Mountains consists of long, wet summers and cold winters. According to the Foping climate station (107°59′E, 33°32′N, 1088 m a.s.l.), the annual mean precipitation and temperature are 910.6 mm and 11.4 °C. With increasing altitude, the vegetation changes from *Quercus variabilis* forest (<1200 and <1400 m on the northern and southern slopes, respectively), *Q. aliena* var. *acuteserrata* forest (1200–1650 m *versus* 1400–2050 m), *Q. mongolica* forest (only on the northern slope, 1650–2300 m), *Betula albo-sinensis* forest (2300–2600 m *versus* 2250–2500 m), *B. utilis* forest (2600–2950 m *versus* 2500–2850 m) to *Abies fargesii* forest (2900–3150 m *versus* 2850–3200 m) and *Larix chinensis* forest (3150–3400 m *versus* 3200–3430 m, forming a climate-induced treeline), to a *Rhododendron capitatum* shrub (>3400 m *versus* >3430 m) (Tang, 2003).

2.2. Measurement of temperature

In order to measure the temperature and its spatial variations at Mt. Taibai, 17 portable HOBO H8 Pro microloggers were installed at different altitudes with an elevation interval of *ca.* 250 m from 1500 to 3750 m along the southern slope and from 1250 to 3750 m along the northern slope (Fig. 1). Prior to and after the measurement, the microloggers were checked in an ice-water bath, which confirmed their remarkable stability and absolute accuracy (deviation from zero <0.2 °C). Microclimatic variables are highly sensitive to changes in the over story canopy and exhibit relatively high spatial and temporal variability within a forest (Morecroft et al., 1998; Chen et al., 1993). To keep the ambient environment as constant as possible, all the microloggers were installed in undisturbed mature forests with nearly the same canopy coverage (70–85%), stem density (533–817 stems/ha), and total basal area (18.2–27.1 m^2/ha) (Table 1). The microloggers were riveted on tree trunks each at a height of 1.5 m above ground level and the sensor were kept on the northwest side of the trees to eliminate direct solar radiation. The altitude of each site was measured using a Barigo altimeter (Barigo Barometerfabrik GmbH, Villingen-Schwenningen, Germany) and checked against 1:50,000 topographic maps. Because the upper altitudes (over *ca.* 3300 m) of this mountain are snow-covered from October to May, the top of the mountain is inaccessible during this period. Thus, the measurement started at 00:00 h of 15 July 2001 and ended at 23:30 h of 5 August 2002. Data were recorded at intervals of 30 min. However, we only used the data between 00:00 h of 1 August 2001 and 23:30 h of 31 July 2002 (a year) for our analysis. During the measurement, the micrologger at 2750 m on the northern slope was damaged, and data from above 3500 m were excluded from the present analysis because vegetation was very sparse and low at these sites (>3400 m) and consisted of alpine shrubs.

Table 1
Elevation (Ele., m a.s.l.), forest type and forest structure [canopy coverage (CC, %), basal area (BA, m^2/ha), stem density (SD stem/ha), average diameter at breast height (DBH, cm), and average tree height (H, m)] around the measurement locations along the northern and southern slopes of Mt. Taibai, Qinling Mountains

	Ele. (m a.s.l.)	Forest type	CC (%)	BA (m^2/ha)	SD (stem/ha)	DBH (cm)	*H* (m)
S-slope	1500	Qa	80	19	617	18.4	10.4
	1780	Qa	80	27	650	21.4	12.8
	2020	Qa	75	20	517	18.5	11.6
	2220	Qa	80	25	567	18.9	10.4
	2450	Ba	75	18	537	18.5	11.6
	2750	Ba	80	26	717	19.4	11.6
	3000	Af	75	19	533	15.6	9.3
	3250	Lc	70	21	578	18.7	9.5
N-slope	1250	Qa	70	18	700	16.4	11.3
	1500	Qa	80	24	767	18.5	13.9
	1750	Qa	80	27	700	20.5	12.4
	2000	Qm	75	21	817	17.3	11.4
	2250	Qm	80	24	617	20.0	9.8
	2500	Ba	75	22	583	22.0	8.9
	3000	Af	85	24	750	18.2	10.5
	3250	Lc	80	24	750	18.0	9.8

Qa, *Quercus aliena* var. *acuteserrata* forest; Qm, *Q. mongolica* forest; Ba, *Betula albo-sinensis* forest; Af, *Abies fargesii* forest; Lc, *Larix chinensis* forest.

2.3. Data analysis

Six temperature parameters were calculated to explore the altitudinal and seasonal variation in temperatures: monthly mean temperature (MMT), annual mean temperature (AMT), monthly mean diurnal range of temperature (MDRT), annual mean diurnal range of temperature (ADRT), annual range of temperature (ART), and accumulated temperature above 0 °C (AT0). The MMT was an average of the daily mean temperature in the month, which was calculated as an average of 48 records (one record per 30 min) observed in a day. The AMT was the average of the MMTs. The MDRT was an average of the diurnal ranges of temperature (DRT) in a month, which was the difference between the daily maximum and minimum temperatures. The ADRT was an average of the MDRTs, and the ART was a difference between the MMTs for the warmest and coldest months. The AT0 was the sum of temperatures for any period in which the daily mean temperature exceeded 0 °C.

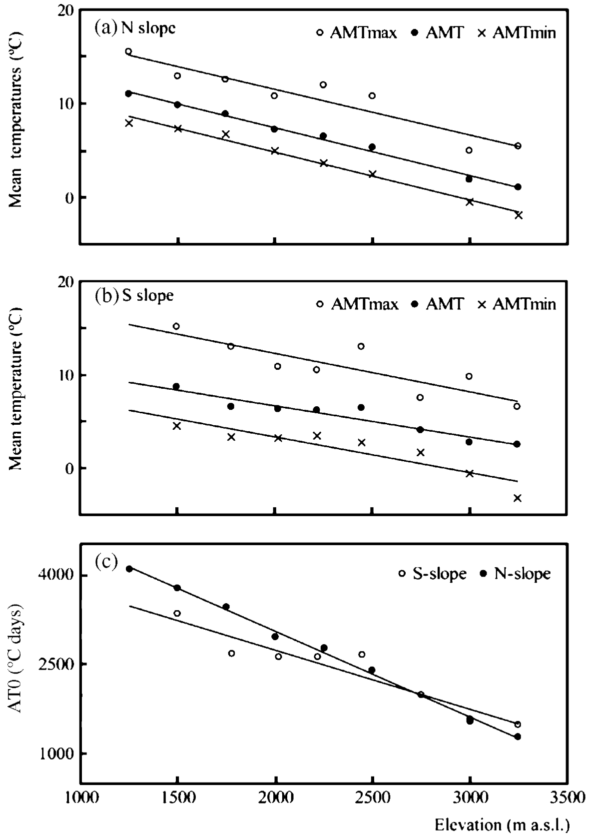

Fig. 2. Variations in annual mean (AMT, °C), mean daily maximum (AMT_{max}, °C) and minimum temperature (AMT_{min}, °C) along (a) the northern and (b) the southern, as well as (c) the accumulated temperature above 0 °C (AT0, °C days) along the northern and southern slopes of Mt. Taibai, Qinling Mountains.

Diurnal variation of lapse rate is another aspect of climatic pattern. To explore this pattern, we calculated the average hourly temperature for different dates between 1 August 2001 and 31 July 2002.

The relationship between these parameters and altitude was evaluated by using a type II regression in Excel.

3. Results

3.1. Mean temperatures

The AMT decreased linearly from 8.7 °C at 1500 m to 2.5 °C at 3250 m with a lapse rate of 0.34 ± 0.04 °C/100 m along the southern slope, and from 11.0 °C at 1250 m to 1.1 °C at 3250 m with a lapse rate of 0.50 ± 0.02 °C/100 m along the northern slope (Fig. 2). AMT_{max} and AMT_{min} also declined linearly, and both had a very close lapse rate: 0.41 ± 0.10 and 0.39 ± 0.07 °C/100 m for the southern slope and 0.49 ± 0.07 and 0.51 ± 0.02 °C/100 m for the northern slope, respectively (Fig. 2a and b).

The AT0 followed a pattern similar to that of the mean temperatures (AMT, AMT_{max} and AMT_{min}); it was 3329 °C days at 1500 m on the southern slope, and decreased linearly to 1490 °C days at 3250 m with a lapse rate of 98.6 ± 13.0 °C days/100 m. Along the

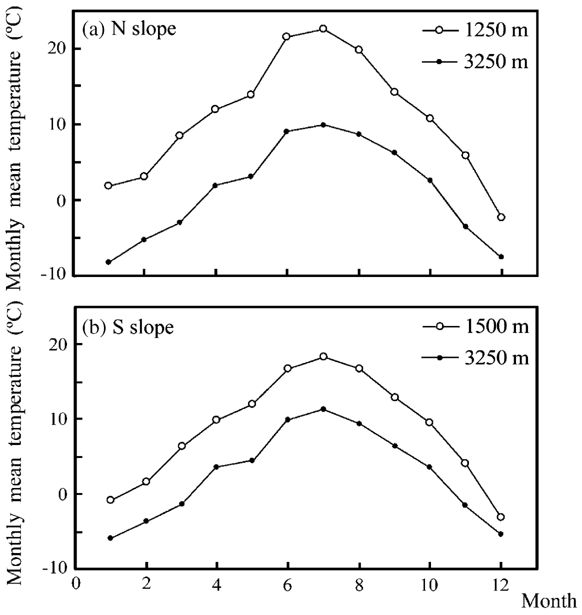

Fig. 3. Variation of monthly mean temperature (MMT, °C) at different elevation on (a) the northern and (b) southern slope of Mt. Taibai, Qinling Mountains.

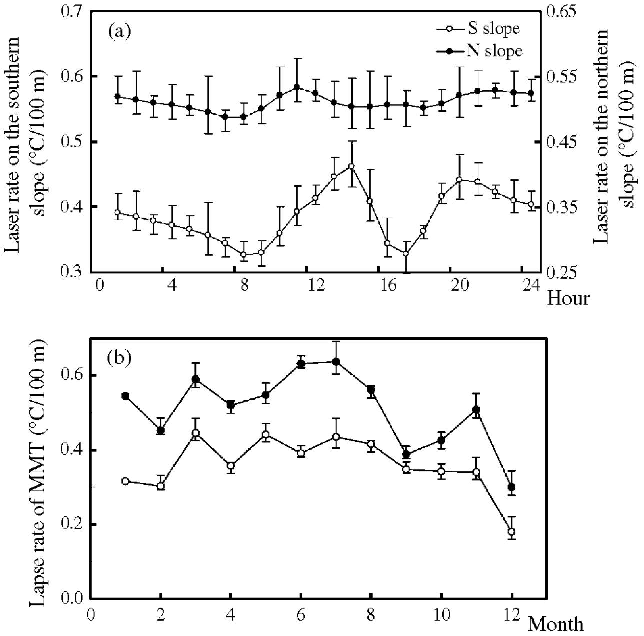

Fig. 4. Diurnal (a) and seasonal (b) variation of lapse rates (°C/100 m) on the northern and southern slopes of Mt. Taibai, Qinling Mountains. The hourly lapse rate in (a) was an average lapse rate of the same time for different dates between 1 August 2001 and 31 July 2002.

northern slope, it was 4075 °C days at 1250 m, and decreased to 1277 °C days at 3250 m, with a lapse rate of 142.5 ± 3.75 °C days/100 m (Fig. 2c).

3.2. Diurnal and seasonal changes in temperatures

The highest MMT appeared in July and the lowest in December for most altitudes on both slopes, but not for an altitude of 3250 m, where the lowest temperature appeared in January. The MMT for July varied between 11.1 °C (at 3000 m) and 18.3 °C (at 1500 m) for the southern slope, and between 9.8 °C (at 3250 m) and 22.5 °C (at 1250 m) for the northern slope. The MMT for December fluctuated from −6.7 °C (at 2750 m) to −3.1 °C (at 1500 m) for the southern slope and from −8.4 °C (at 3000 m) to −2.3 °C (at 1250 m) for the northern slope (Fig. 3). At an altitude of *ca.* 3000 m, a temperature inversion was observed in winter from November 2001 to February 2002 for the southern slope, and from December 2001 to February 2002 for the northern slope.

Altitudinal lapse rates of temperature varied significantly in the day (Fig. 4a). As showed in Fig. 4a, the lapse rate both for the northern and southern slopes was highest at noon (12 a.m. and 2 p.m. for the northern and southern slopes) and lowest in the morning (both at 8 a.m.). The altitudinal lapse rates of MMT varied seasonally, with a range of 0.14–0.43 °C/100 m for the southern slope and 0.29–0.63 °C/100 m for the northern slope. The highest lapse rate occurred in March (0.43 ± 0.05 °C/100 m) or May (0.42 ± 0.05 °C/100 m) for the southern slope and in June and July (both 0.63 ± 0.02 °C/100 m) for the northern slope, while the lowest both in December (0.14 ± 0.05 °C/100 m and 0.29 ± 0.03 °C/100 m, respectively) (Fig. 4b). As depicted in Fig. 4, the lapse rates for all the time and all months were higher on the northern than on the southern slope, perhaps because the northern slope has a much drier climate than the southern slope.

3.3. Diurnal and annual ranges of temperature

The ADRT fluctuated between 5.8 °C (2750 m) and 10.5 °C (1500 m) for the southern slope and between 5.5 °C (3000 m) and 8.4 °C (2250 m) for the northern

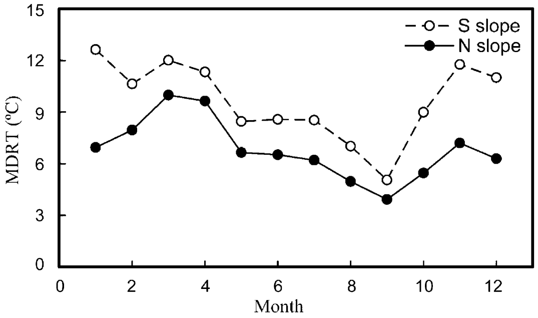

Fig. 5. Monthly variation of average diurnal range of temperature (MDRT, °C) on the northern and southern slopes of Mt. Taibai, Qinling Mountains.

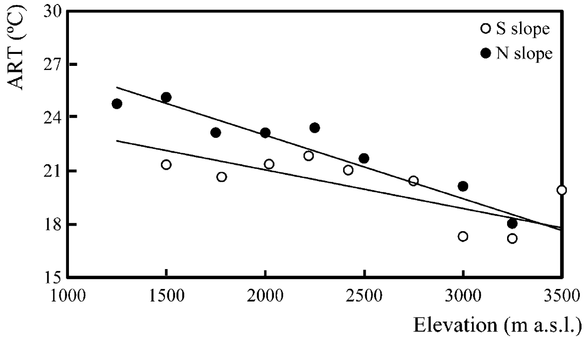

Fig. 6. Variation in annual range of temperature (ART, °C) along the northern and southern slopes of Mt. Taibai, Qinling Mountains.

slope (Fig. 5). It did not exhibit any significant elevational trends, due mainly to the similar lapse rate of the AMT_{max} and AMT_{min} on both the northern and southern slopes (Fig. 2a and b). Seasonally, larger MDRTs were observed in winter and spring (from November to the next April) than in September for the southern slope. Such a seasonal pattern was also shown on the northern slope, but for all the months, the ranges (MDRT) were smaller than on the southern slope (Fig. 5).

The difference between the MMT for the warmest and the coldest months, ART, sharply decreased with increasing elevation for both northern and southern slopes according to the following rule:

$$R_n = -0.0032H + 29.5 \quad (R^2 = 0.91) \tag{1}$$

$$R_s = -0.0024H + 25.9 \quad (R^2 = 0.64) \tag{2}$$

where R_n and R_s are the ART for the northern and southern slopes, respectively, and H is the altitude in meter.

In contrast to the MDRT and ADRT, the ARTs for all the altitudes on the southern slope were lower than those on the northern slope (Fig. 6).

4. Discussion

4.1. Comparison between the microloggers and long-term observation

Using the climate records from meteorological stations around the study area is another way to analyze the relationship between climate and topography (Huntley et al., 1989). To compare the present study with long-term observation, we analyzed the relationship between station-observed temperature and altitude, latitude and longitude by using a multiple regression: MAT = a × latitude + b × longitude + c × altitude + d (Fang and Yoda, 1988). The long-term observations were from 36 meteorology stations (19 from the southern slope and 17 from the northern slope) within and around the Qinling Mountains, with a latitudinal and longitudinal range of 32-35°30′N, and 104-113°E, respectively. The results showed that the monthly lapse rate was higher on the northern slope than on the southern slope, and higher in summer than in winter (Tang, 2003), consistent with the data from the microloggers in the present study. By using these relationships, we calculated the MATs of the observation site of the present study, which were close to the actual data from observation (Fig. 7). This suggests that the data collected through HOBO data loggers represents the long-term pattern in the Qinling Mountains.

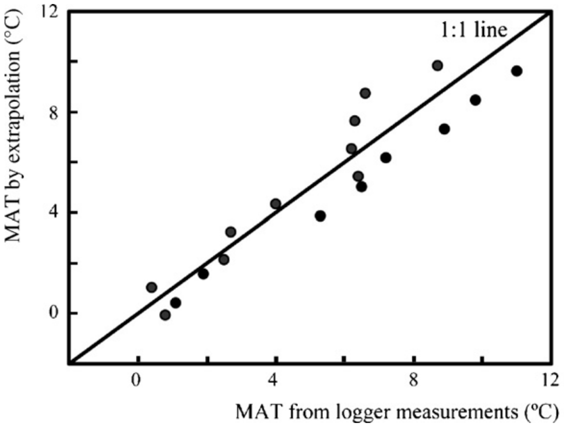

Fig. 7. Comparison between the MAT (°C) measured by loggers and the MAT extrapolated using multiple regression against long-term observations.

4.2. Comparison between the southern and northern slopes

Altitudinal lapse rates of temperatures are one of the important characteristics of local and regional climate, and they change with macro topography, movement of air masses, latitude and distance from the sea coast (Pepin, 2001; Barry, 1992; Fang, 1992; Yoshino, 1975). Generally, they are lower in humid conditions than in dry areas (Pepin, 2001). The lower lapse rate of AMT on the southern slope than on the northern slope observed in the present study (Fig. 5) supports this widely accepted conclusion, because the climate is moister on the southern than on the northern slopes in the Qinling Mountains (Li and Fu, 1984). This can be evidenced from the Shiquan station (108°16′E, 33°03′N, 484.9 m a.s.l.) and the Xi'an station (108°56′E, 34°02′N, 397.5 m a.s.l.) that the climate is more humid on the southern than on the northern slopes of the Qinling Mountains (with an annual precipitation of 569.0 mm *versus* 913.8 mm for the northern and southern slopes). The higher ART on the northern slope is also consistent with the pattern identified in the changes in the lapse rate of the AMT, because ART is usually regarded as a surrogate of oceanic/continental climate and a higher ART suggests a more continental-like climate (Barry, 1992). In other words, the climate is more continental on the northern than on the southern slopes in the Qinling Mountains. The difference between the northern and southern slopes was more pronounced at lower elevations and less pronounced at higher elevations.

4.3. Application of the climatic pattern in vegetation study

Altitudinal lapse rates of temperatures showed considerable seasonal changes on both slopes in the Qinling Mountains, with a higher value in summer than in winter (Fig. 4). This is a general pattern in East Asia (Fang, 1992) and is consistent with many other studies (Richardson et al., 2004; Rolland, 2003; Bolstad et al., 1998; Barry, 1992). Such seasonal changes in lapse rates should be taken into account when estimating climatic indices, which are used to analyse the relationships between plant/vegetation distribution and climatic conditions (e.g., Pendry and Proctor, 1996; Ohsawa, 1990; Huntley et al., 1989).

In the Qinling Mountains, the elevational ranges of primary vegetation types vary significantly between the northern and the southern slopes (Tang, 2003). To explore the factors determining the distribution of vegetation types, we calculated the climatic ranges of each type by extrapolating climatic data such as the MAT, the mean temperature of the growing season (MTGS, defined as the period with daily average temperature >5 °C), and the MMT, using the lapse rates derived from the above analysis. The results showed that for the same vegetation type, MTGS exhibited the same range on the northern and southern slope, indicating that MTGS was the primary factor controlling elevational distribution of vegetation types at Mt. Taibai. For example, the oak (*Quercus variabilis*, *Q. aliena* var. *acuteserrata*, and *Q. mongolica*) forests occurred in areas with MTGS > 11 °C. Birch (*Betula albo-sinensis* and *B. utilis*) forests had an MTGS > 9 °C, and coniferous (*A. fargesii* and *L. chinensis*) forests had an MTGS > 7.5 °C.

The location of the alpine treeline is generally considered to be driven by growing season air temperatures, although small-scale variation in treeline elevation may be due to a multitude of other factors, such as topography, aspect, wind and winter snow accumulation (Körner, 1998). Several thermal indices have been proposed to predict the elevation of treelines, such as mean temperature of 10 °C for the warmest month (MTWM) (Troll, 1973), a MTGS of 5.5–7.5 °C (Körner and Paulsen, 2004), a growing season length of approximately 100 days (Ellenberg, 1963), and warmth index (WI) of 15 °C month [$\mathrm{WI} = \sum(t_i - 5\,^{\circ}\mathrm{C})$, where t_i represents the monthly mean temperature when it exceeds 5 °C] (Kira, 1991; Ohsawa, 1990). In the Qinling Mountains, the alpine treeline is located at an altitude of about 3430 m on the southern slope and 3400 m on the northern slope (Tang, 2003). For each of the measuring sites, we calculated the above thermal indices, and then the relationships between elevation and these thermal indices using type II regression. By using these relationships, we extrapolated the MTWM, MTGS, growing season length, and WI at the timberline; they are 9.04 and 10.8, 7.5 and 7.7 °C, 114 and 135 days, and 11.0 and 15.1 °C month on the northern and southern slopes, respectively. The MTWM, growing season length and WI at the timberline showed significant differences between the northern and southern slopes, while the MTGS was very close on both slopes, suggesting that MTGS is probably a better indicator for interpreting the altitude of the timberline in the Qinling Mountains. This is consistent with other studies both in China (Wang et al., 2004) and around the world (Körner and Paulsen, 2004).

5. Concluding remarks

The elevational gradient of climates is a base for understanding the relationship between climate and vegetation in mountainous areas. In the present study, we used temperature microloggers to measure the temperature over a year at 16 sites along the northern and southern slopes of Mt. Taibai, the highest mountain in eastern mainland China. The results indicated that the lapse rates of mean temperatures showed significant temporal and spatial variations; they were higher in the summer than in the winter and on the northern than on the southern slopes. The diurnal range of temperature (DRT) was higher on the southern than on the northern slope, whereas the annual range of temperature (ART) showed a higher value on the northern than on the southern slope. These findings are valuable in analysing the vegetation patterns in mountainous areas. In the Mt. Taibai, the growing season thermal conditions are likely to be the primary factors controlling the distribution of vegetation types, as each primary vegetation types showed identical mean temperature during the growing season (MTGS) on the northern and southern slopes despite the different altitudinal ranges. Our results suggested that seasonal patterns of temperature lapse rates should be taken into account for analysis of vegetation-climate relationships in mountainous areas.

Acknowledgements

The authors thank J.H. Ke and L. Zhang for their assistance in the fieldwork, and anonymous reviewers for the constructive comments. This project was supported by the Natural Science Foundation of China (#40501025, 49971002, 90211016, and 40228001) and the State Key Basic Research and Development Plan of China (no. G200004681). Thanks also to the Gottlieb Daimler—Karl Benz Foundation for the fellowship awarded to Zhiyao Tang (17-04/01) towards studying at the University of Hanover.

References

Barry, R.G., 1992. Mountain Weather and Climate, 2nd ed. Routledge, London.

Beniston, M., Diaz, H.F., Bradley, R.S., 1997. Climatic change at high elevation sites: an overview. Climatic Change 36, 233–251.

Bolstad, P.V., Swift, L., Lollins, F., Regniere, J., 1998. Measured and predicted air temperatures at basin to regional scales in the southern Appalachian Mountains. Agric. Forest Meteorol. 91, 161–176.

Chen, J., Franklin, J.F., Spies, T.A., 1993. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agric. Forest Meteorol. 63, 219–237.

Ellenberg, H., 1963. Vegetation Mitteleuropas mit den Alpen in kausaler, dynamischer und historischer Sicht. Ulmer, Stuttgart.

Fang, J.Y., 1992. Studies on geographic distribution of the altitudinal lapse rate of temperature in China. Chin. Sci. Bull. 37, 1979–1983.

Fang, J.Y., Yoda, K., 1988. Climate and vegetation in China. I. Changes in the altitudinal lapse rate of temperature and distribution of sea level temperature. Ecol. Res. 3, 37–51.

Friedland, A.J., Boyce, R.L., Vostral, C.B., Herrick, G.T., 2003. Winter and early spring microclimate within a mid-elevation conifer forest canopy. Agric. Forest Meteorol. 115, 195–200.

Hasenauer, H., Merganicova, K., Petritsch, R., Pietsch, S.A., Thornton, P.E., 2003. Validating daily climate interpolations over complex terrain in Austria. Agric. Forest Meteorol. 119, 87–107.

Huntley, B., Bartlein, P.J., Prentice, I.C., 1989. Climatic control of the distribution and abundance of beech (*Fagus* L.) in Europe and North America. J. Biogeogr. 16, 551–560.

Juvik, J.O., Nullet, D., Banko, P., Hughes, K., 1993. Forest climatology near the treeline in Hawaii. Agric. Forest Meteorol. 66, 159–172.

Kira, T., 1991. Forest ecosystems of East and Southeast Asia in a global perspective. Ecol. Res. 6, 185–200.

Körner, Ch., 1998. A re-assessment of high elevation treeline positions and their explanation. Oecologia 115, 445–459.

Körner, Ch., Paulsen, J., 2004. A world-wide study of high altitude treeline temperatures. J. Biogeogr. 31, 713–732.

Li, Z.Y., Fu, B.P., 1984. Climatic characteristics in the Qinling Mountains. In: Compilation group (Eds.), Collected paper on mountain climates. Chinese Meteorological Publishing House, Beijing, pp. 87–96.

Lookingbill, T.R., Urban, D.L., 2003. Spatial estimation of air temperature differences for landscape-scale studies in montane environments. Agric. Forest Meteorol. 114, 141–151.

Morecroft, M.D., Taylor, M.E., Oliver, H.R., 1998. Air and soil microclimates of deciduous woodland compared to an open site. Agric. Forest Meteorol. 90, 141–156.

Nullet, D., Juvik, J.O., Wall, A., 1995. A Hawaii mountain climate cross section. Climate Res. 5, 131–137.

Ohsawa, M., 1990. An interpretation of latitudinal patterns of forest limits in South- and East-Asian mountains. J. Ecol. 78, 326–339.

Pendry, C., Proctor, J., 1996. The causes of altitudinal zonation of rain forests on Bukit Belalong, Brunei. J. Ecol. 84, 407–418.

Pepin, N., 2001. Lapse rate changes in northern England. Theor. Appl. Climatol. 68, 1–16.

Richardson, A.D., Lee, X., Friedland, A.J., 2004. Microclimatology of treeline spruce-fir forests in mountains of the northeastern United States. Agric. Forest Meteorol. 125, 53–66.

Rolland, C., 2003. Spatial and seasonal variations of air temperature lapse rates in Alpine regions. J. Climate 16, 1032–1046.

Tang, Z., 2003. Patterns of plant species diversity in the Qinling Mountains, Central China. Doctoral thesis, Peking University.

Troll, C., 1973. The upper timberline in different climatic zones. Arctic Alpine Res. 5, 3–18.

Wang, X.P., Zhang, L., Fang, J.Y., 2004. Geographical differences in alpine timerline and its climatic interpretation in China. Acta Geogr. Sin. 59, 871–879.

Xia, Y., Fabian, P., Stohl, A., Winterhalter, M., 1999. Forest climatology, estimation of missing values for Bavaria, Germany. Agric. Forest Meteorol. 96, 131–144.

Yoshino, M., 1975. Climate in a Small Area. University of Tokyo Press, Tokyo.