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Spatial and temporal temperature trends on the Yunnan Plateau (Southwest China) during 1961–2004

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ABSTRACT: Monthly mean (TEM), maximum (T_{max}) and minimum (T_{min}) surface air temperatures at 119 meteorological stations on the Yunnan Plateau (YP, Southwest China) were analysed for temporal trends and spatial variation patterns during the period 1961–2004. Linear trend analyses revealed that annual temperature over the YP increased at a rate of 0.3 °C/decade during the period 1961–2004, while warming trend of 0.33 °C/decade and 0.26 °C/decade was observed for winter and summer temperatures, respectively. Warming trends of nighttime minimum temperature are more pronounced than those of daytime maximum temperature, especially during winter season. Consequently, a decreasing trend of diurnal temperature ranges (DTR = $T_{max} - T_{min}$) was observed. Five spatial patterns of temperature variability were objectively defined by rotated empirical orthogonal function (EOF) analysis, which are associated with distinct temporal temperature variations and geographical area over the YP. Annual temperature increases were found to be most pronounced in the southern and northwestern (high-elevation) parts of the YP, whereas the hot-dry valleys along the Yangtze and Red River basins experienced cooling during the past four decades. Copyright © 2010 Royal Meteorological Society

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KEY WORDS climate change; global warming; temperature; trend analysis; Yunnan Plateau

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1. Introduction

Climate change is potentially challenging the food production, drinking water supply and sustainable development in many parts of the world (IPCC, 2007). Recent studies revealed a significant worldwide warming and a general increase in frequency and persistence of high temperatures (Easterling *et al.*, 2000; Horton *et al.*, 2001; Yan *et al.*, 2002; Beniston and Stephenson, 2004; Gay-Garcia *et al.*, 2009). The global mean surface air temperature has risen by about 0.74 ± 0.18 °C during the twentieth century and is projected to rise by $1.8 \sim 4.0$ °C in the twenty-first century (Brohan *et al.*, 2006; IPCC, 2007). During the period 1880–2003, the linear rise of mean temperature over China is 0.58 °C/100 years, which is slightly weaker than that of the global mean (Wang and Gong, 2000). However, the warming trend (0.3 °C/decade) during the past two decades in China is much stronger than the global trend (0.19 °C/decade) (Wang *et al.*, 2004; Hansen *et al.*, 2006).

Mountainous and highland regions are especially sensitive and vulnerable to climate change (Beniston *et al.*, 1997; Diaz and Bradley, 1997). For example, above-average warming trends were observed at higher elevations (i.e. elevation-dependency warming) on a global scale (Diaz and Bradley, 1997) or at a more regional scale such as in the Swiss Alps (Beniston and Rebetez, 1996), on the Tibetan Plateau (Liu and Chen, 2000; Liu *et al.*, 2006, 2009) and in the Tien Shan Mountains (Aizen *et al.*, 1997). Another important feature associated with climatic warming noted by many scientists is its asymmetric nature over the daily cycle, with less warming observed in maximum temperature than in minimum temperature (Karl *et al.*, 1993; Liu *et al.*, 2009). As a result, over the vast land area of the world, the near-surface diurnal temperature range (DTR) has been decreasing (Easterling, 1997). On the Tibetan Plateau, greater warming trends were found in monthly minimum temperature (0.41 °C/decade) than that of maximum temperature (0.18 °C/decade) during the period 1961–2003 (Liu *et al.*, 2006).

Many studies investigated climate changes and extremes on a very large scale (Easterling *et al.*, 2000; Miranda and Tome, 2009) or at national levels (Bartolini *et al.*, 2008; Filipiak and Mietus, 2008; Brazdil *et al.*,

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2009; Brito-Castillo *et al.*, 2009). However, there are large regional differences in the surface air temperature change (Houghton *et al.*, 2001). The Intergovernmental Panel on Climate Change (IPCC) highlighted the need for more detailed information about climate change on regional and local scales, which is of particular interest to nations and economic groups and often dense homogeneous historical datasets are available (IPCC, 2007).

Many researchers (e.g. Wang and Gong, 2000; Qian and Zhu, 2001; Liu *et al.*, 2004; Huang *et al.*, 2005) have investigated the changes of temperature over the past decades in China. The accelerated climate warming observed since the 1980s and its associated impacts have already been studied extensively (Yi *et al.*, 1992; Ding and Dai, 1994; Shi *et al.*, 2007). On a regional scale, an overall warming trend was found over the Tibetan Plateau during 1955–1996 (Liu and Chen, 2000). However, a cooling trend of annual mean temperature with a decrease of the daily maximum temperatures since the mid-twentieth century was observed in the Sichuan Basin, Southwest China (Ban *et al.*, 2006; Ding *et al.*, 2007).

Yunnan is a densely populated province in southwestern China and is the home of many ethnic groups that often live in ecologically fragile mountain regions. The northern part of Yunnan is characterized by a very steep topography and consists of mountain chains higher than 6000 m a.s.l. which are dissected by deeply incised gorges of main Asian rivers like the Mekong and Salween rivers. Climatic changes in this area will have a strong impact not only on the position of the upper tree line (Baker and Moseley, 2007) and on the hydrological cycle, which is of great relevance for agriculture and forestry (Stone, 2010), but also for geomorphological activity and the risk of flooding during the summer monsoon season.

On the low-latitude Yunnan Plateau (YP), climatic variability is largely unknown. Thomas (1993) studied the temporal and spatial characteristics of the onset of the rainy season during the period 1961–1980. Using data from a number of representative stations, Chen and Xie (2008) and Yang *et al.* (2007) analysed climatic changes in the recent 50 years over Yunnan Province and found that most stations display warming trends, with a decrease of annual snow days in the north and annual fog days in the south. On the basis of an extensive dataset from 119 meteorological stations from Yunnan Province in southwestern China, this study aimed to examine the spatial and temporal temperature variability over the YP during the period 1961–2004. Particular emphasis was put on investigating the overall warming trend and its spatial variability. Special attention was laid on trends of seasonal developments of temperature variability and trends.

2. Data and methods

2.1. Study area

The YP is situated in subtropical Southwest China and covers an area of about 394 000 km^2 between 21.14 and 29.25 °N and 97.52–106.19 °E, contiguous to the

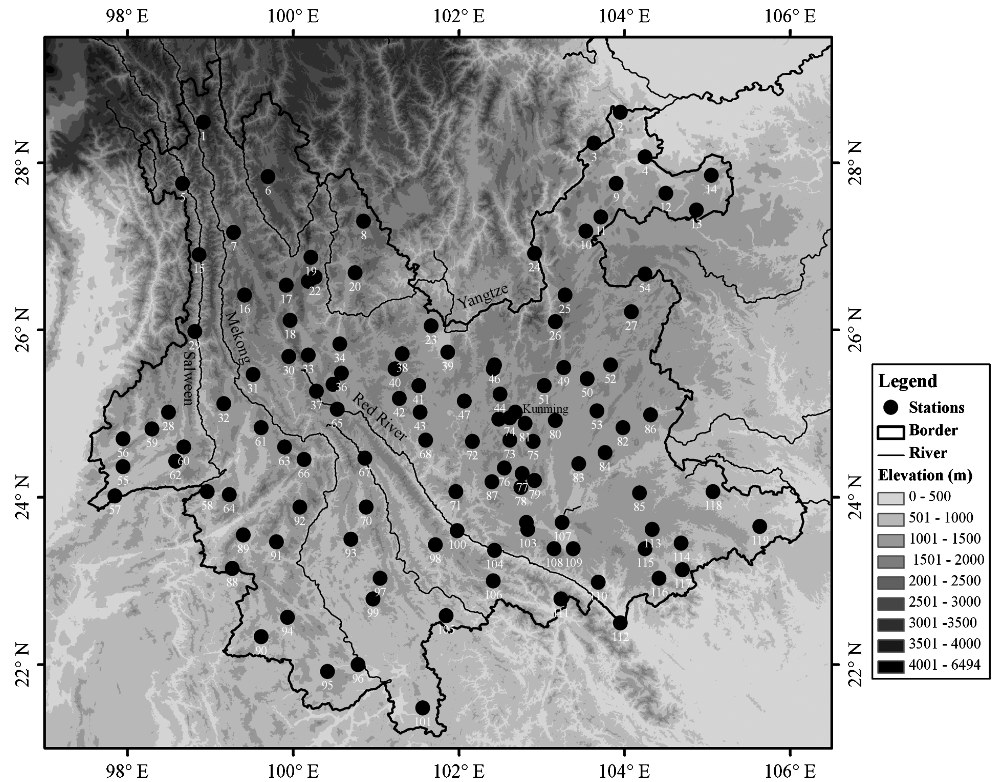

Figure 1. Locations of the 119 meteorological stations on the Yunnan Plateau. Data are from the National Meteorological Information Centre (NMIC). Topographical views of the Yunnan Plateau and vicinity are also embodied (TOPO30, http://www.usgs.gov). Station numbers below the data points are consistent with those in Table S1.

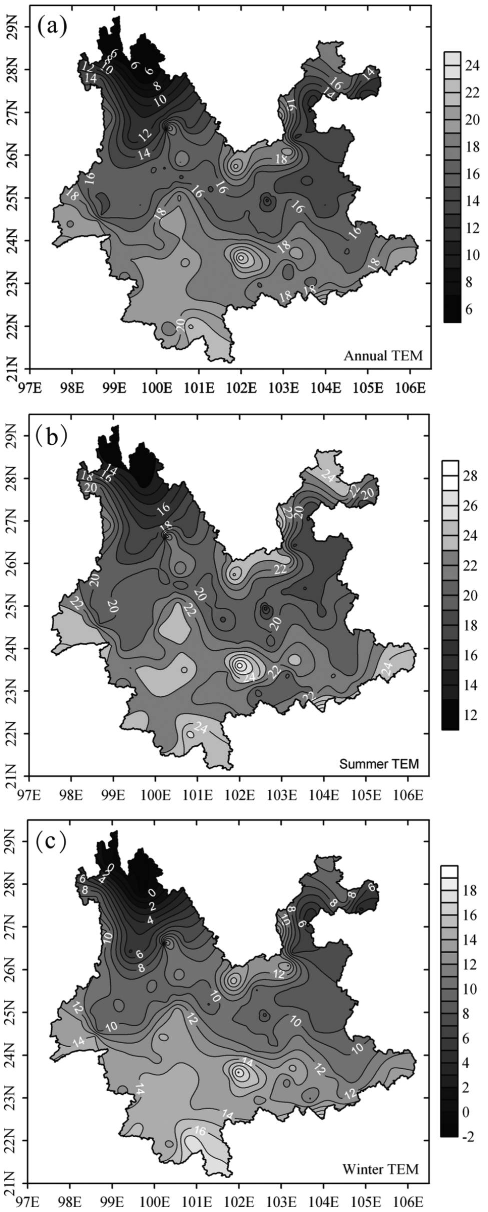

Figure 2. Geographical distribution of the annual (a), summer (b), June to September and winter (c), November to February mean air temperature (TEM, °C) over the Yunnan Plateau. Mean values were calculated over the period of 1961–2004 and interpolated with the Kriging method.

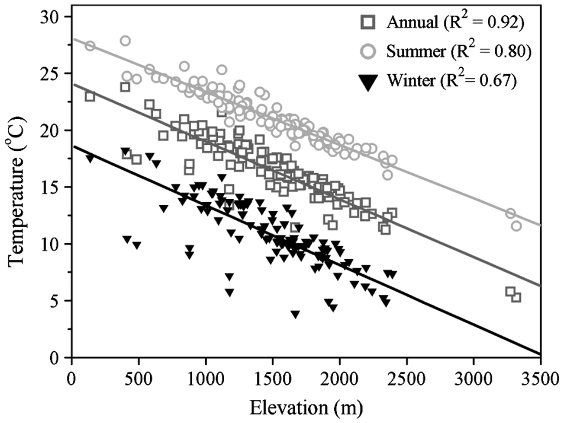

Figure 3. Relationships between annual and seasonal mean temperatures (°C) and elevation (m). Linear regressions and their statistics are embodied in the graphs.

Tibetan Plateau in the northwest and the Sichuan Basin in the north (Figure 1). The YP is a mountainous area with an average altitude of 1980 m, with the high mountains of eastern Himalayas in the west. Within Yunnan Province, elevation decreases from the northwest with the highest point of 6740 m a.s.l. to the southeast with the lowest point of 76.4 m a.s.l. The YP climate is influenced by the interaction of several circulation systems. Summer climate over the YP is co-dominated by the Southwest and East Asian summer monsoons during June to September, whereas the climate condition during winter is influenced by northern continental cold air masses and extra-tropical westerlies (Thomas, 1993). Because of the low-latitude location and the pronounced topography with the deep river-carved gorges, the YP climate is subjected to intense solar radiation and mild air temperatures with a large diurnal amplitude, little annual variation and tremendous spatial variability.

2.2. Dataset

Instrumental data of monthly mean (TEM), maximum (T_{max}) and minimum (T_{min}) surface air temperatures were used in this study. The mean monthly maximum and minimum temperatures are derived by averaging the daily maximum and minimum temperatures. The mean monthly DTR is defined as the difference between the mean monthly maximum and minimum temperatures ($T_{max} - T_{min}$). Most of the meteorological stations in Yunnan Province were not established until the mid-1950s. Therefore, the time period considered is from 1961 to 2004. Data were collected from a total of 133 weather stations from the National Meteorological Information Centre (NMIC) of China. For each station, we carefully checked the time periods of records and relocation histories. Of the 133 stations, 14 stations were excluded from further analyses due to discontinuities of data (11 stations) or inhomogeneities due to relocation (3 stations). Thus, the 119 remaining stations entered the final analyses (Figure 1, Table S1).

The dataset have been quality checked by the NMIC. We further performed routine quality assessment and necessary error correction procedures on the data following the methods described by Peterson *et al.* (1998). Missing values are infrequent and generally account for only 0.2–0.4% (Table S2), which were replaced with estimated values predicted from multiple regression relationships established among a few (up to five) neighbouring and highly correlated stations. The 119 stations are well-distributed across the YP, except in the west (Figure 1). The station identification number prescribed by the World Meteorological Organization (WMO) and the station name along with their coordinates, are listed in Table S1. The altitudes of all 119 stations vary between 136.7 m (Hekou) and 3319 m (Deqin), with 102 (86%)

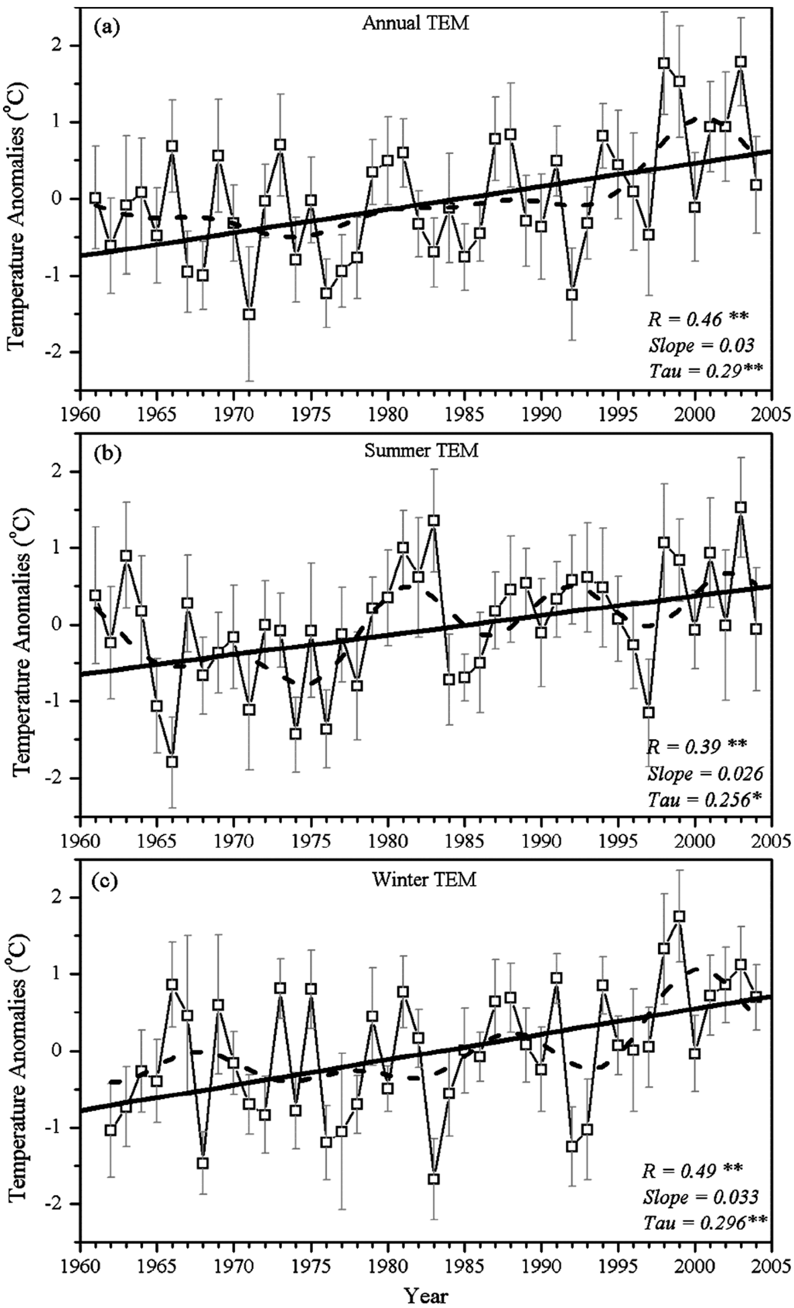

Figure 4. Regional averaged annual (a), summer (b) and winter (c) temperatures for the period 1961–2004 derived from all 119 stations over the Yunnan Plateau. The straight line shows the linear trend, and the dashed line represents 10-year low-pass filter components. *R* and *Slope* represent the correlation coefficient and the slope of linear regression, respectively. *Tau* is the Mann–Kendall tau rank correlation coefficient. The * and ** represent significance at 95 and 99% level, respectively.

stations situated above 1000 m a.s.l. and 14 (12%) stations are above 2000 m a.s.l.

2.3. Seasonality and spatial distribution

Annual, summer (June to September) and winter (November to February) temperature means were calculated from monthly data. Spatial distributions of annual and seasonal temperatures were interpolated with the Kriging method using the software Surfer (version 8.0). In order to reveal topographic effects on temperature distributions, annual and seasonal temperatures for all the 119 stations were also correlated with their elevations.

To facilitate trend analyses and comparisons between the stations, we calculated temperature anomalies from the long-term monthly means to remove the seasonality. Monthly and seasonal temperature anomalies were averaged over the YP and were correlated with time (year/months) to detect overall trends.

2.4. Trends detection

An ordinary linear regression (OLR) $\hat{y} = \alpha t + \beta$ is used to estimate the rate of change α, with $\hat{y}$ being the monthly and seasonal temperatures analysed and t is the time (here the year/month). The 44-year time series of

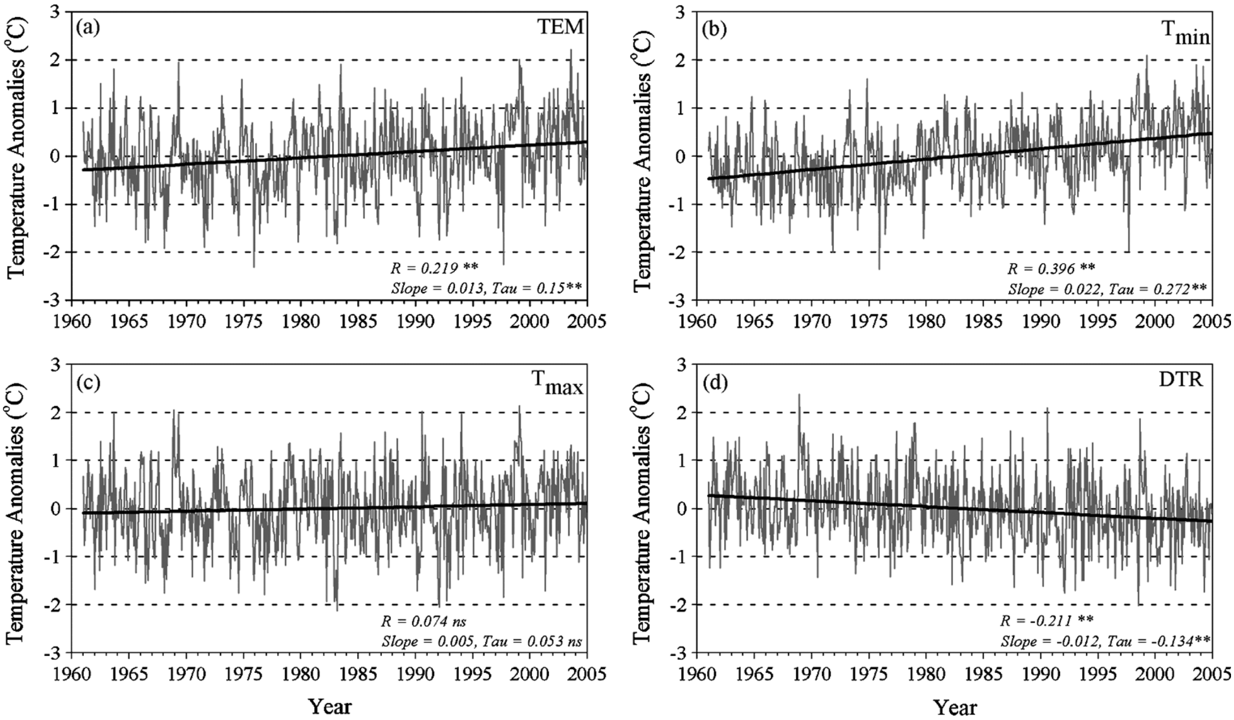

Figure 5. Monthly mean temperature anomalies (grey lines) and their linear trends (thick lines) averaged for the study area from January 1961 to December 2004. (a) Mean temperature (TEM), (b) minimum temperature (T_{min}), (c) maximum temperature (T_{max}), (d) diurnal temperature range (DTR). *R* and *Slope* represent the correlation coefficient and the slope of linear regression, respectively. *Tau* is the Mann–Kendall tau rank correlation coefficient. The ** and *ns* indicate 99% significance level and no significant trend, respectively.

Table I. Statistics of linear trends (slope, °C/decade) of seasonal temperatures averaged for all the 119 meteorological stations over the Yunnan Plateau.

	Season	Mean	SD	Increasing	Decreasing	R_{alt}	R_{lat}	R_{lon}
Mean Temperature	Annual	0.12	0.12	76 (64%)	7 (6%)	0.10	−0.29**	−0.06
	Summer	0.08	0.11	55 (46%)	7 (6%)	0.13	−0.36**	−0.06
	Winter	0.22	0.15	81 (68%)	1 (0.8%)	0.05	−0.19*	0.09
Minimum Temperature	Annual	0.22	0.16	93 (78%)	2 (1.7%)	0.14	−0.19*	−0.18*
	Summer	0.14	0.11	79 (66%)	3 (2.5%)	0.14	−0.18	−0.06
	Winter	0.31	0.20	93 (78%)	1 (0.8%)	0.08	−0.12	−0.14
Maximum Temperature	Annual	0.06	0.10	33 (28%)	6 (5%)	0.21*	−0.13	−0.03
	Summer	0.03	0.10	21(18%)	9 (8%)	0.19*	−0.26*	−0.10
	Winter	0.18	0.11	25 (21%)	0 (0%)	0.26**	0.03	0.24**

The correlation coefficients between station trends and their coordinates are also indicated.
SD is the standard deviation of the regression slopes; increasing/decreasing are the numbers (percentages) of stations shown significant ($p < 0.05$) increasing/decreasing linear trend; R_{alt}, R_{lat} and R_{lon} are correlation coefficients between the regression slopes and altitudes, latitudes and longitudes, respectively.
The * and ** represent significance at 95 and 99% level, respectively.

monthly and seasonal temperatures of all 119 stations were regressed against time. The statistical significance of the linear trends was evaluated using the Student's *t-test*. The magnitude of the trends was calculated by the slopes of the linear trends and expressed in °C/decade. All the data analyses were carried out using the free-accessed R data processing and analysis language (R Development Core Team, 2004).

Additionally, the Mann–Kendall non-parametric test, which searches for a trend in a time series without specifying whether the trend is linear or non-linear, was also applied to each time series to look for statistically significant trends (Mann, 1945; Kendall, 1975; Yue and Wang, 2004). The Mann–Kendall tau rank correlation coefficients and their significance tests were calculated using the 'Kendall' package in the R environment. Spatial distributions of the linear trends (slopes, °C/decade) were interpolated on the map using the ArcMap software (version 9.0). Monthly and seasonal temperature trends (slopes) were averaged over the study area and correlated with the elevations of the respective climate stations.

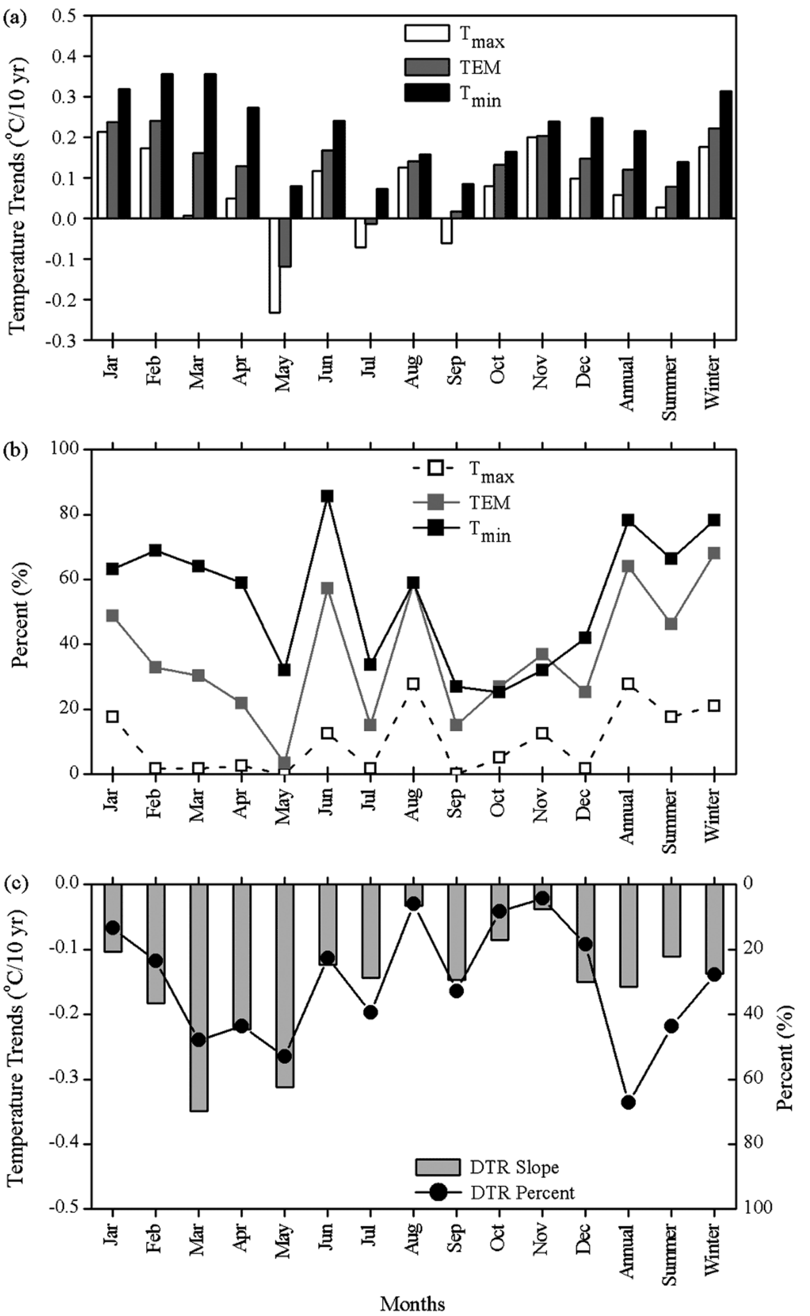

Figure 6. Statistics of linear regression trends for monthly and seasonal mean (TEM), maximum (T_{max}), minimum (T_{min}) temperatures and diurnal temperature ranges (DTR) during the period 1961–2004. (a) Trends (regression slopes) averaged for the study area; (b) percentages of stations shown positive significant ($p < 0.05$) linear trends; (c) trends (bars) and percentages (dot-lines) of stations shown negative significant ($p < 0.05$) trends for DTR.

2.5. Empirical orthogonal function analyses

Empirical orthogonal function (EOF) analysis has been widely used in meteorology and climatology to define spatial and temporal variability of a large set of variables (Richman, 1986; Briffa *et al*., 1994; Hannachi *et al*., 2009). The correlation-based varimax-rotated empirical orthogonal function (REOF) method is used in this study. This means that the initial EOF modes are linearly transformed using the varimax method, which maximizes the variance of the squared correlation coefficient between the time series of each REOF mode and each original EOF model. The method increases the spatial variability of the obtained modes. Therefore, the significant anomalies appear where regional phenomena are dominant, which makes the mode easier to interpret (Richman, 1986).

In this study, the 'variables' refer to the 119 stations, and the 'observations' are the annual temperatures for each station during 1961–2004. Determining the number of EOF modes to be rotated is an important issue in REOF analysis, as it directly affects the resulting spatial patterns and temporal variations, facilitating or misleading the search of physical interpretations. We performed a rigorous 'red noise' version of the Rule N test (Preisendorfer, 1988; Li *et al.*, 2008a), which is based on the Monte Carlo procedure. The first five EOFs (or factors), which explained nearly 90% of the total variance, were found to be significant at the 95% confidence level, according to the Rule N test (Preisendorfer, 1988). Therefore, the five EOFs were rotated to produce five clearly defined spatial patterns over the YP.

3. Results

3.1. Spatial temperature distributions

Owing to the topographical complexity, this study region displays a wide variety of micro-climates. Figure 2 presents the spatial distributions of averaged annual and seasonal air temperatures over the YP during 1961–2004. The mean annual temperatures ranged from 4.3 to 24 °C, while temperatures varied from 10 to 31 °C and from −2.4 to 21 °C during summer (June to September) and winter season (November to February), respectively. In the high-elevation area of the northwest YP, temperature gradients are more abrupt than in the other regions (Figure 2). The statistics of coefficient of variance and skewness indicated homogeneous distribution of the climate data, except for the topogeographic complex of northwest YP (Table S3, Figure S1 and S2). The north and central parts of Yunnan along the Yangtze and Red Rivers is the so-called 'hot-dry valleys' region, with a character of high temperature and low precipitation. Air temperatures generally decrease by 0.47–0.52 °C/100 m elevation increase, which corresponds to a moist-adiabatic trend (Figure 3). For winter, more negative departures from the trend line are visible in the lower elevations. This probably is related to the stations located in mountain basins and valleys, where cold air accumulates during the winter season, leasing to topography-induced pronounced minimum temperatures.

3.2. Temporal and spatial temperature trends

Over the YP, mean annual temperatures have been increasing by 0.3 °C/decade during the past 44 years (Figure 4). The warming rates during winter (0.33 °C/decade) were greater than that during summer season (0.26 °C/decade). The overall warming on the YP started around the end of 1970s and accelerated after 1990s. For annual temperature means, 15 of 24 years were above the long-term average after 1978.

Concerning the monthly normalized anomalies, both mean (TEM) and minimum ($T_{\min}$) temperature anomalies showed a significant ($p < 0.01$) positive trend over the YP (Figure 5), equivalent to a rate of 0.13 °C/decade and 0.22 °C/decade, respectively. However, no significant trend was found for maximum temperature ($T_{\max}$) anomalies. Consequently, the anomalies of DTR ($T_{\max} - T_{\min}$) had been decreasing significantly ($p < 0.01$), equivalent to −0.12 °C/decade (Figure 5(d)). The Mann–Kendall statistics are consistent with results from linear regressions.

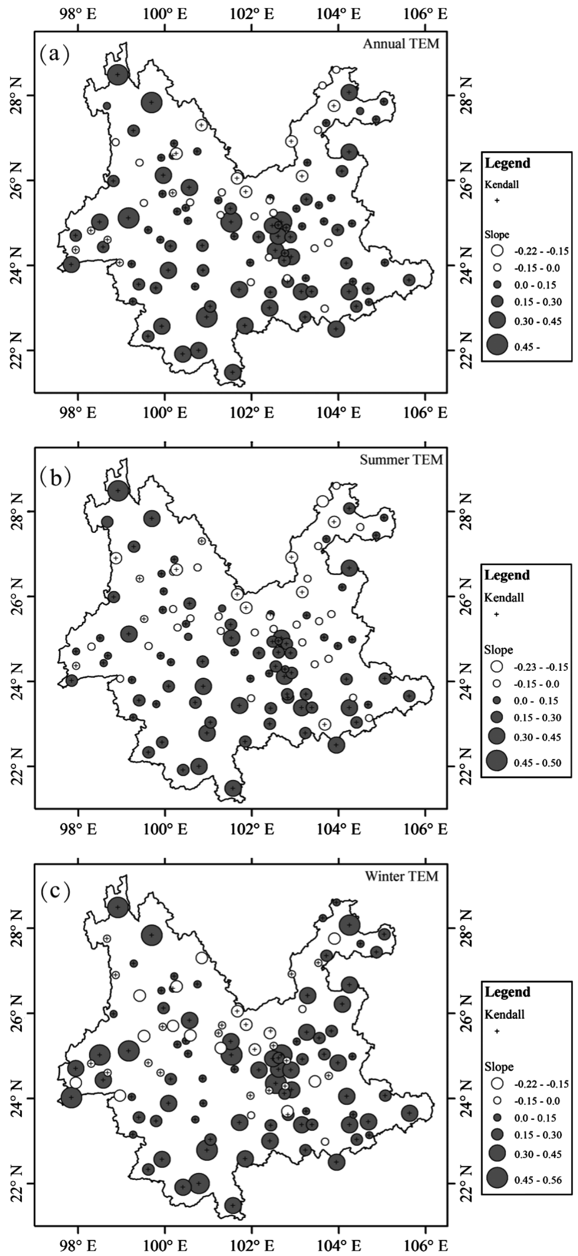

Figure 7. Spatial patterns of annual (a), summer (b) June to September and winter (c) November to February air temperature linear trends (TEM, °C/decade) over the Yunnan Plateau for the period 1961–2004. Stations with significant (95%) Mann–Kendal trend test are also indicated.

More than 46 and 66% of the 119 stations show significant warming trends for mean (TEM) and minimum ($T_{\min}$) temperatures, respectively (Table I, Figure 6). However, there are fewer stations (20–30%) showing a significant warming trend for maximum temperatures ($T_{\max}$). More stations with significant warming trends were found during winter than during the summer season. As a result, DTRs over the past 44 years had been decreasing. Especially, the decreasing trends of DTR during the spring season are most remarkable (Figure 6(c)).

Figures 7 and 8 present the spatial distributions of linear trends (slopes, °C/decade) of annual and seasonal

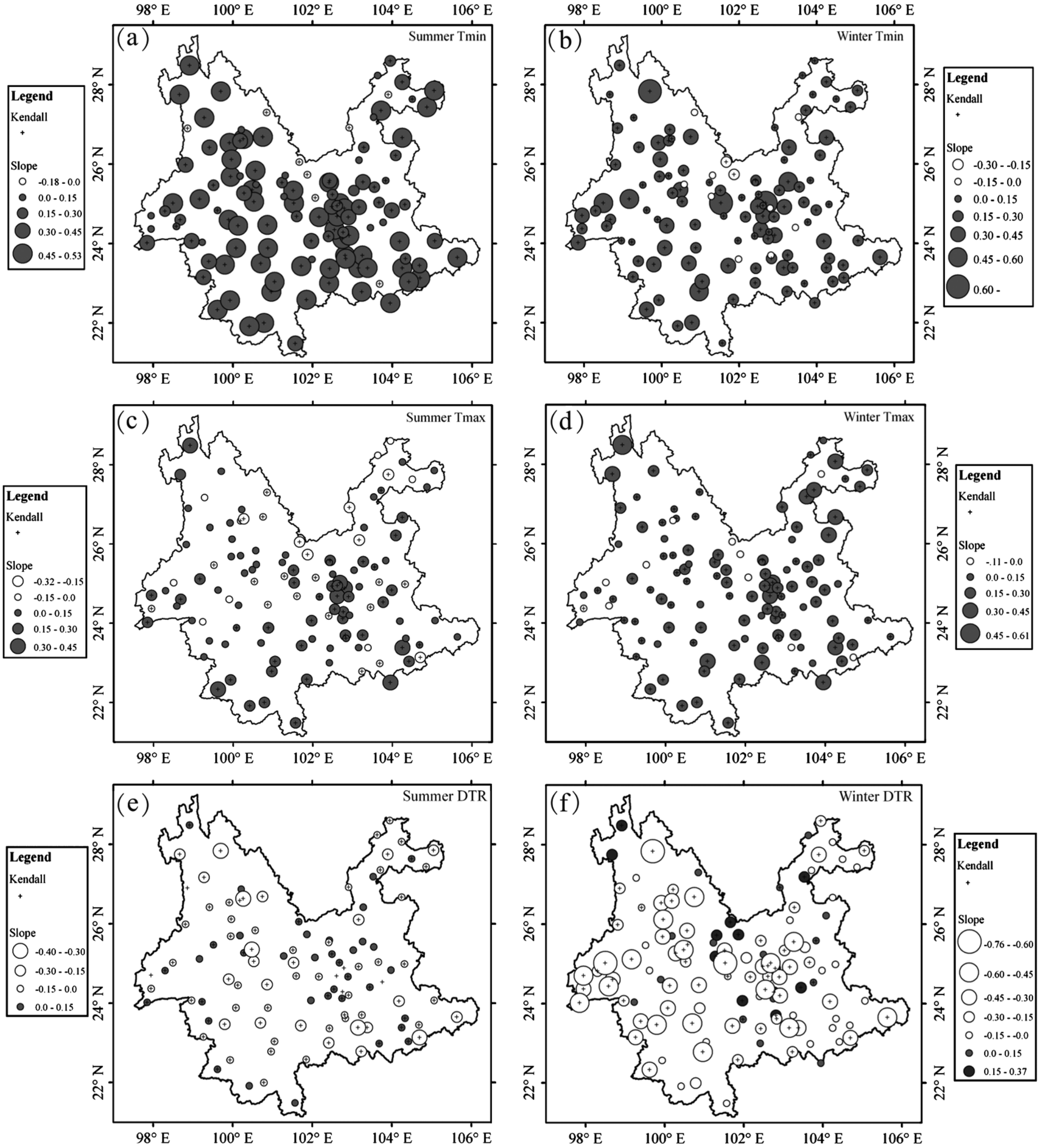

Figure 8. Spatial patterns of the linear trends (°C/decade) of monthly mean minimum ($T_{\min}$; a, b) and maximum ($T_{\max}$; c, d) air temperatures and diurnal temperature range (DTR; e, f) during the summer (a, c, e; June to September) and winter (b, d, f; November to February) seasons. The linear trends were calculated for data of all 119 meteorological stations during the period 1961–2004. Stations with significant (95%) Mann–Kendal trend test are also indicated.

air temperatures over the YP for the period 1961–2004. A non-parameter Mann–Kendall test was performed to detect the non-monotonic trends. Over the past 44 years, annual and winter temperatures increased over the majority of the plateau. The picture of summer temperatures looks different, with most positive trends found for stations south of ∼26 °N (Figure 7). The most striking and regional wide warming trends were found for monthly minimum temperatures, both for the summer and winter seasons (Figure 8(a) and (c)). The magnitudes of warming trends for maximum temperatures were less than that of mean and minimum temperatures, especially during the summer season (Figure 8(b), (d)). Again, DTRs at most stations were decreasing during the past 44 years (Figure 8(e) and (f))

When temperature trends were arranged by the elevation zones, we did not find a clear elevation dependency of climatic warming from low to middle elevations. However, the high-elevation stations in the northwestern part of the YP show a remarkably high rate of warming (Figure 9).

3.3. Regional patterns of temperature variability

REOF analysis was used to objectively define the most significant regional patterns of annual temperature variability across YP. Regional patterns of temperature

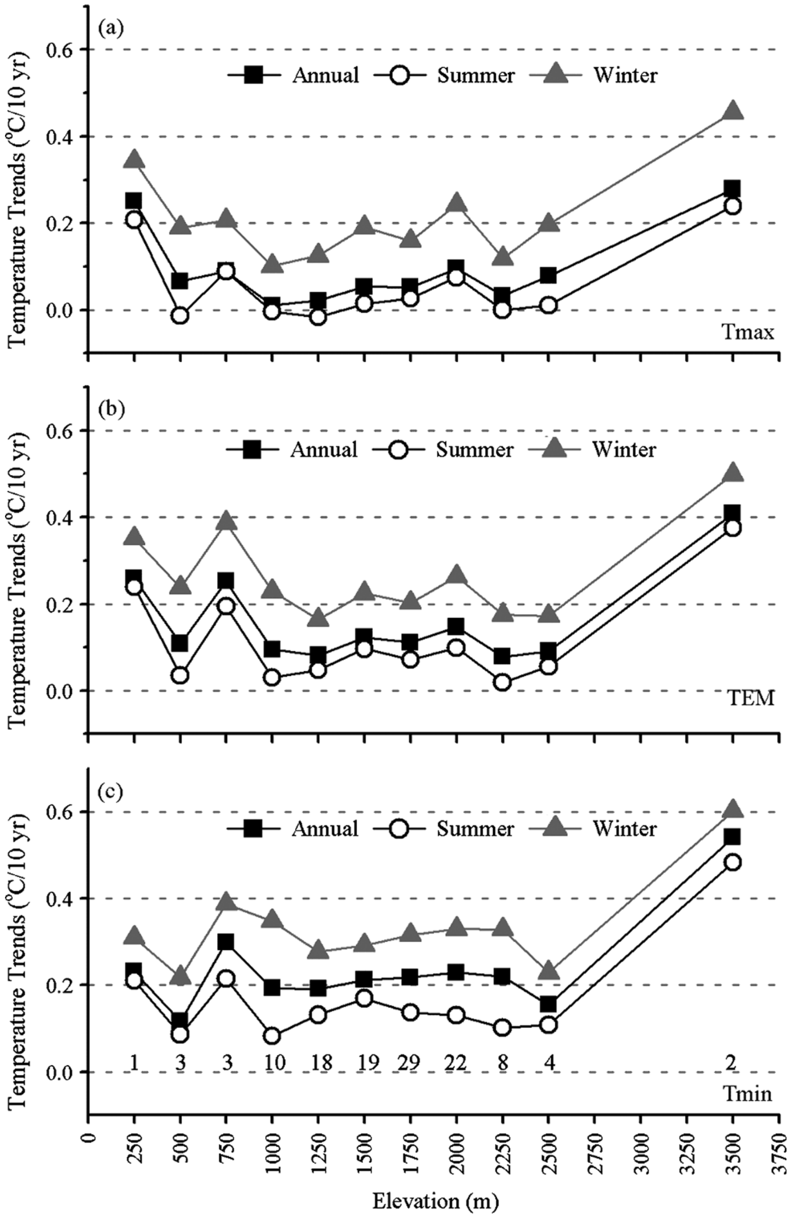

Figure 9. Annual and seasonal temperature trends (°C/decade) for the period 1961–2004, categorized according to the 14 elevation ranks of the 119 stations on the Yunnan Plateau. Number of stations for each elevation rank is indicated in the lower part of the graph.

variability are defined in terms of the factor maps and the associated scores from the orthogonal varimax rotations (Figure 10).

REOF#1 represents the temperature variability in the southwestern and central parts of the YP (SW–C pattern). This pattern explains 25.86% of the total temperature variance (Table II). The score for this pattern shows a decreasing temperature during the 1960s, and then a continuous warming since the middle of the 1970s. The warming trend (0.42 °C/decade) in the SW–C pattern during 1961–2004 is statistically significant at the 0.01 level. The warmest year is 2003, followed by 1998 and 1999, which is consistent with the ground means of annual temperature over the YP (Figure 4(a)).

REOF#2 explains 17.75% of the total temperature variance and highlights the common temperature variability over the northeastern and eastern parts of the YP (NE–E pattern). The score associated with this pattern shows no significant trend during the study period. However, the warmest years 1998 and 2003 were detectable in the NE–E pattern.

REOF#3 is heavily loaded over the northwestern part of the YP (NW pattern) and explains 17.48% of the total variance. The score shows a continuous warming trend (0.37 °C/decade) since the beginning of the 1960s and greater variability (i.e. extremely cold/warm years) during the past two decades.

REOF#4 describes temperature variability in the southeastern and southern parts of YP (SE–S pattern). This pattern explains 15.39% of the total variance. The score exhibits a temperature jump at the end of the 1970s and a continuous warming trend thereafter. The overall

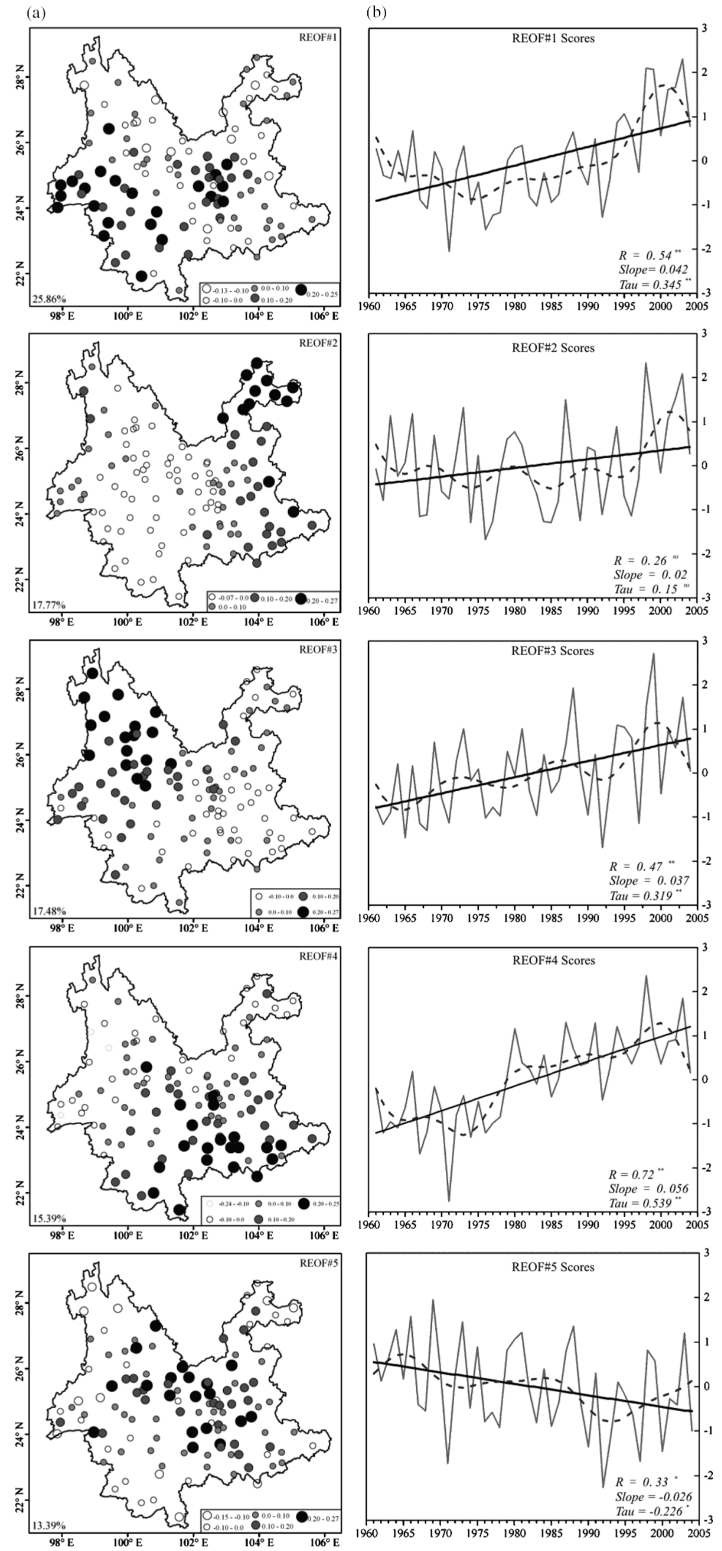

Figure 10. The five factor loadings (a) and their corresponding normalized REOF scores (b) based on rotated REOF analysis on annual temperatures for the period 1961–2004. The percentage variance accounted for by each factor is labelled in each map. Linear regression (bold) and 10-year low-pass filters (dashed) are applied for the REOF scores. *R* and *Slope* represent the correlation coefficient and the slope of linear regression, respectively. *Tau* is the Mann–Kendall tau rank correlation coefficient. The * and ** indicate significance at 95 and 99% level respectively, the *ns* is no significant trend.

warming trend (0.56 °C/decade) in this region is greatest compared with other regions of the YP.

REOF#5 represents the temperature variability in the central and northern parts of the YP (C–N pattern), along the Yangtze River and Yuanjiang River (upper Red River) valleys. This pattern explains the least (13.39%) of the total variance. The score of the C–N pattern reveals a significant decreasing trend (−0.26 °C/decade,

Table II. The variance explained by the first five factors derived from empirical orthogonal functions (EOF) on annual and seasonal mean temperatures before and after the Varimax rotation.

Component	Annual		Summer		Winter	
	Unrotated EOF (%)	Rotated EOF (%)	Unrotated EOF (%)	Rotated EOF (%)	Unrotated EOF (%)	Rotated EOF (%)
1	64.79	25.86	59.56	22.23	69.70	25.80
2	11.07	17.75	11.33	19.41	11.19	25.80
3	7.64	17.48	6.66	18.79	5.95	19.73
4	3.73	15.39	5.70	15.55	3.49	15.49
5	2.63	13.39	3.02	10.28	2.37	5.89
Total	89.9	89.9	86.3	86.3	92.7	92.7

$p < 0.01$), which is distinct from other regions of the study area.

4. Discussion

A statistically significant warming trend (0.3 °C/decade for annual temperature) was detected for the YP during the period 1961–2004, with stronger warming in the winter season than in the summer season (Figure 4, Table I). The overall warming rates over the YP exceed global means (0.14 °C/decade; Brohan *et al*., 2006) and the mean of the same latitudinal zone for the same period (Diaz *et al*., 2003; Jones and Moberg, 2003; Gay-Garcia *et al*., 2009). The warming trends over the YP are even more pronounced than those for China means (∼0.26 °C/decade; Zhai *et al*., 1999; Liu *et al*., 2004; Wang *et al*., 2004; Huang *et al*., 2005) and are comparable with those found on the Tibetan Plateau (Liu and Chen, 2000; Liu *et al*., 2006).

The increase (less change) in monthly minimum (maximum) temperatures on the YP, as found in the present study (Figures 5–8), are broadly consistent with global patterns (e.g. Karl *et al*., 1993; Easterling, 1997; Easterling *et al*., 2000) and the results from most areas of China (Zhai *et al*., 1999; Yan *et al*., 2002, Liu *et al*., 2006). However, some studies found a faster rate of increase in maximum temperatures, resulting in increasing trends of DTR, such as in north India (Yadav *et al*., 2004) and Mexico (Brito-Castillo *et al*., 2009). The downward trend of DTR over the YP is jointly caused by the distinct positive trend in minimum temperature and less changes in maximum temperature. Strongly increasing trends of minimum temperature can be found in all seasons, with the highest increasing trends in winter and spring, resulting in the distinct decreasing trend of DTR during winter and spring season (Figures 6–8). Decreasing strength of winter monsoon (Asian high pressure) may result in positive winter trend, especially of minimum temperatures (Wang *et al*., 2009). Moreover, the increasing tropospheric aerosol load in the study area may attribute to the observed decreasing sunshine duration as well as the increasing of nighttime temperature (Zheng *et al*., 2008).

Because of the complex topography, the climatic trends and variability over the YP are far from uniform. Despite the overall warming, the warming rates are different in different regions over the YP (Figure 10). Most significant warming was found in the southern and northwestern (high-elevation) parts of the YP (Figure 10), whereas the dry valleys along the Yangtze and Red River basins experienced a cooling trend during the past decades (Figures 7, 8 and 10). In the southern parts of the YP, forests have been degraded at a fast rate, which has accelerated carbon emissions and thus climate changes. For example, forest cover had been reduced from 70% in 1976 to less than 50% in 2003 in the Xishuangbanna area, and the forested areas have mainly been replaced by rubber (*Hevea brasiliensis*) plantations and shifting cultivation (Li *et al*., 2008b). Moreover, large-scale land-cover changes from primary rainforests to rubber tree plantation are likely to alter regional emission patterns of volatile organic compounds (VOCs), which in turn might contribute to changes in regional air quality and climate (Wang *et al*., 2007; Wilske *et al*., 2007).

Consistent with the present study, Zhang *et al*. (2002) found that the annual mean temperature in the Yuanmou valley of Yunnan has declined by 1.1 °C from 1956 to 1999, accompanied by a slight increase in annual rainfall. The landscapes of the dry valleys are a striking geographic feature in the Hengduan Mountains Region of Southwest China. They are characterized by an extremely steep topography and elevation deference between valley floor and neighbouring mountain ranges of more than 3000 m, resulting in low rainfall, high temperature and evaporation and a fragile environment with slopes covered by drought-tolerant vegetation types (Tang *et al*., 2004). Many of the dry valleys have been centres of economic and agricultural development and human settlement. The increase in rainfall and the decline in temperatures and evaporation may benefit the local agricultural production in the hot-dry valleys of Yunnan (Zhang *et al*., 2002; Tang *et al*., 2004).

Significant decreases in sunshine duration were found over most of the 200 stations across China during 1954–1998, with greatest concentration over southwestern China near the Sichuan basin (Kaiser and Qian, 2002). The downward trend in sunshine duration may result from negative radiative forcing due to increasing atmospheric aerosol concentrations from regional pollutants, which was suggested to be the main contributor to surface cooling during the latter half of the twentieth century in the Sichuan basin and vicinity (Qian and Giorgi, 2000; Ban *et al*., 2006). It is argued that a decline in solar irradiance better explains the decreasing range of daily temperatures in light of its influence on maximum temperature. Consistent with our results (Figures 7 and 8), Zheng *et al*. (2008) found that the annual sunshine duration on the Yunnan–Guizhou Plateau decreased mostly north of 24 °N during 1961–2005.

Many studies from observational data (Beniston and Rebetez, 1996; Diaz and Bradley, 1997; Liu and Chen, 2000) and numerical modelling (Giorgi *et al*., 1997; Chen *et al*., 2003) have revealed the elevation dependency of climate warming in regions of major mountains and highlands. In the present study, the dependence of temperature trends on elevations is incoherent, which differs from previous findings on the Tibetan Plateau, north west of the study area (Liu and Chen, 2000; Liu *et al*., 2009). It is noteworthy that most of our meteorological stations are located at middle elevations between 1000 and 2000 m a.s.l., where the elevation effect may not be so prominent. This is corroborated by the finding of a remarkably strong warming at the high-elevation stations (Deqin and Zhongdian, >3000 m a.s.l.) in the northwest of the YP (Figure 9, Table S1).

5. Conclusion remarks

In this study, annual and seasonal temperatures (mean, minimum and maximum) were investigated for their spatial and seasonal trends and variability, based on a dataset of 119 meteorological stations over the YP during 1961–2004. Regional annual temperature has risen by 0.3 °C/decade during the past 44 years. The warming trends were found to be more pronounced during the winter season from November to February, whereas summer warming is mostly confined to the south part of the YP. Regional warming trends in monthly minimum temperatures are more prominent than increase of maximum temperatures. Greater and more consistent warming was found in the south and northwest (high-elevation) area of the YP, but less in the east. In contrast, the hot-dry valleys of the Great Asian Rivers experienced a cooling trend during the past decades.

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References

Aizen VB, Aizen EM, Melack JM, Dozier J. 1997. Climatic and hydrologic changes in the Tien Shan, Central Asia. *Journal of Climate* **10**: 1393–1404.

Baker BB, Moseley RK. 2007. Advancing treeline and retreating glaciers: implications for conservation in Yunnan, P.R. China. *Arctic, Antarctic and Alpine Research* **39**: 200–209.

Ban J, Miao Q, Li X. 2006. Analysis of characteristics of temperature variations in southwest China in recent 50 years. *Resources Environment in the Yangtze Basin* **15**(3): 346–351 (in Chinese with English abstract).

Bartolini G, Morabito M, Crisci A, Grifoni D, Torrigiani T, Petralli M, Maracchi G, Orlandini S. 2008. Recent trends in Tuscany (Italy) summer temperature and indices of extremes. *International Journal of Climatology* **28**: 1751–1760, DOI: 10.1002/joc.1673.

Beniston M, Diay HF, Bradley RS. 1997. Climate change at high elevation sites: an overview. *Climatic Change* **36**: 233–251.

Beniston M, Rebetez M. 1996. Regional behavior of minimum temperatures in Switzerland for the period 1979–1993. *Theoretical and Applied Climatology* **53**: 231–243.

Beniston M, Stephenson DB. 2004. Extreme climatic events and their evolution under changing climatic conditions. *Global and Planetary Change* **44**: 1–9, DOI: 10.1016/j.gloplacha.2004.06.001.

Brazdil R, Chroma K, Dobrovolny P, Tolasz R. 2009. Climate fluctuations in the Czech Republic during the period 1961–2005. *International Journal of Climatology* **29**: 223–242, DOI: 10.1002/joc.1718.

Briffa KR, Jones PD, Hulme M. 1994. Summer moisture variability across Europe 1892–1991: an analysis based on the Palmer drought severity index. *International Journal of Climatology* **14**: 475–506, DOI: 10.1002/joc.3370140502.

Brito-Castillo L, Castro SCD, Herrera RSU. 2009. Observed tendencies in maximum and minimum temperatures in Zacatecas, Mexico and possible causes. *International Journal of Climatology* **29**: 211–221, DOI: 10.1002/joc.1733.

Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD. 2006. Uncertainty estimates in regional and global observed temperature change: A new data set from 1850. *Journal of Geophysical Research-Atmospheres* **111**: D12106, DOI: 10.1029/2005JD006548.

Chen B, Chao WC, Liu X. 2003. Enhanced climatic warming in the Tibetan Plateau due to doubling CO_2: a model study. *Climate Dynamics* **20**(4): 401–413, DOI: 10.1007/s00382-002-0282-4.

Chen J, Xie M. 2008. The analysis of regional climate change features over Yunnan in recent 50 years. *Progress in Geography* **27**: 19–26 (In Chinese with English abstract).

Diaz HF, Bradley RS. 1997. Temperature variations during the last century at high elevations sites. *Climatic Change* **36**: 253–279.

Diaz HF, Grosjean M, Graumlich L. 2003. Climate variability and change in high elevation regions: past, present and future. *Climatic Change* **59**: 1–4.

Ding Y, Dai Y. 1994. Temperature variations in China over the last one hundred years. *Meteorology* **20**: 19–26 (in Chinese).

Ding Y, Ren G, Zhao Z, Xu Y, Luo Y, Li Q, Zhang J. 2007. Detection, causes and projection of climate change over China: an overview of recent progress. *Advances in Atmospheric Sciences* **24**: 954–971, DOI: 10.1007/s00376-007-0954-4.

Easterling DR. 1997. Maximum and minimum temperature trends for the global. *Science* **277**: 364–367, DOI: 10.1126/science.277.5324.364.

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO. 2000. Climate extremes: observations, modeling and impacts. *Science* **289**: 2068–2074.

Filipiak J, Mietus M. 2008. Spatial and temporal variability of cloudiness in Poland, 1971–2000. *International Journal of Climatology* **29**(9): 1294–1311, DOI: 10.1002/joc.1777.

Gay-Garcia C, Estrada F, Sanchez A. 2009. Global and hemispheric temperatures revisited. *Climatic Change* **94**: 333–349, DOI: 10.1007/s10584-008-9524-8.

Giorgi F, Hurrell JW, Marinucci MR, Beniston M. 1997. Elevation dependency of the surface climate change signal: a model study. *Journal of Climate* **10**(2): 288–296.

Hannachi A, Jolliffe IT, Stephenson DB. 2009. Empirical orthogonal functions and related techniques in atmospheric science: a review. *International Journal of Climatology* **27**(9): 1119–1152, DOI: 10.1002/joc.1499.

Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M. 2006. Global temperature change. *Proceedings of the National Academy of Sciences of the United States of America* **103**(39): 14288–14293, DOI: 10.1073/pnas.0606291103.

Horton EB, Folland CK, Parker DE. 2001. The changing incidence of extremes in worldwide and central England temperatures to the end of the twentieth century. *Climatic Change* **50**(3): 267–295.

Houghton TJ, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA. 2001. *Climate Change 2001: The Science Basis*. Cambridge University Press: Cambridge, New York, 881.

Huang M, Peng GB, Leslie LM, Shao XM, Sha WY. 2005. Seasonal and regional temperature changes in China over the 50 year period 1951–2000. *Meteorology and Atmospheric Physics* **89**: 105–115, DOI: 10.1007/s00703-005-0124-0.

IPCC. 2007. Summary for policymakers. In *Climate Change 2007: The Physical Science Basis*, Contribution of working group I to the Forth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, New York, 1–18.

Jones PD, Moberg A. 2003. Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. *Journal of Climate* **16**(2): 206–223.

Kaiser DP, Qian Y. 2002. Decreasing trends in sunshine duration over China for 1954–1998: indication of increased haze pollution? *Geophysical Research Letters* **29**(21): 2042, DOI: 10.1029/2002GL016057.

Karl TR, Jones PD, Knight RW, Kukla G, Plummer N, Razuvayev V, Gallo KP, Lindseay J, Charlson RJ, Peterson TC. 1993. A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature. *Bulletin of the American Meteorological Society* **74**: 1007–1023.

Kendall MG. 1975. *Rank Correlation Methods*, 4th edn. Griffin: London, 202.

Li J, Cook ER, D'Arrigo R, Chen F, Gou X. 2008a. Moisture variability across China and Mongolia: 1951–2005. *Climate Dynamics* **32**(7–8): 1173–1186, DOI: 10.1007/s00382-008-0436-0.

Li HM, Ma YX, Aide TM, Liu WJ. 2008b. Past, present and future land-use in Xishuangbanna, China and the implications for carbon dynamics. *Forest Ecology and Management* **255**: 16–24, DOI: 10.1016/j.foreco.2007.06.051.

Liu X, Chen B. 2000. Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology* **20**: 1729–1742.

Liu X, Cheng Z, Yan L, Yin ZY. 2009. Elevation dependency of recent and future minimum surface air temperature trends in the Tibetan Plateau and its surroundings. *Global and Planetary Change* **68**(3): 164–174, DOI: 10.1016/j.gloplacha.2009.1003.1017.

Liu BH, Xu M, Henderson M, Qi Y, Li YQ. 2004. Taking China's temperature: daily range, warming trends, and regional variations, 1955–2000. *Journal of Climate* **17**(22): 4453–4462.

Liu XD, Yin ZY, Shao XM, Qin NS. 2006. Temporal trends and variability of daily maximum and minimum, extreme temperature events, and growing season length over the eastern and central Tibetan Plateau during 1961–2003. *Journal of Geophysical Research-Atmospheres* **111**: D19109, DOI: 10.1029/2005JD006915.

Mann HB. 1945. Nonparametric tests against trend. *Econometrica* **13**: 245–259.

Miranda PMA, Tome AR. 2009. Spatial structure of the evolution of surface temperature (1951–2004). *Climatic Change* **93**: 269–284, DOI: 10.1007/s10584-008-9540-8.

Peterson TC, Easterling DR, Karl TR, Groisman P, Nicholls N, Plummer N, Torok S, Auer I, Boehm R, Gullett D, Vincent L, Heino R, Tuomenvirta H, Mestre O, Szentimrey T, Salinger J, Forland EJ, Hanssen-Bauer I, Alexandersson H, Jones P, Parker D. 1998. Homogeneity adjustments of in situ atmospheric climate data: a review. *International Journal of Climatology* **18**: 1493–1517.

Preisendorfer RW. 1988. *Principal Component Analysis in Meteorology and Oceanography*. Elsevier: London.

Qian Y, Giorgi F. 2000. Regional climatic effects of anthropogenic aerosols? The case of southwestern China. *Geophysical Research Letters* **27**(21): 3521–3524.

Qian WH, Zhu JH. 2001. Climate change in China from 1880 to 1998 and its impact on the environmental condition. *Climatic Change* **50**: 419–444.

R Development Core Team. 2004. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, ISBN 3-900051-07-0.

Richman MB. 1986. Rotation of principal components. *International Journal of Climatology* **6**: 293–335, DOI: 10.1002/joc.3370060305.

Shi Y, Shen Y, Kang E, Li D, Ding Y, Zhang G, Hu R. 2007. Recent and future climate change in northwest China. *Climatic Change* **80**: 379–393, DOI: 10.1007/s10584-006-9121-7.

Stone R. 2010. Severe drought puts spotlight on Chinese dams. *Science* **327**: 1311.

Tang Y, Xie J, Sun H. 2004. Revisiting sustainable development of dry valleys in Hengduan Mountains Region. *Journal of Mountain Science* **1**(1): 38–45, DOI: 10.1007/BF02919358.

Thomas A. 1993. The onset of the rainy season in Yunnan province, PR China and its significance for agricultural operations. *International Journal of Biometeorology* **37**: 170–176, DOI: 10.1007/BF01212626.

Wang SW, Gong DY. 2000. Enhancement of the warming trend in China. *Geophysical Research Letters* **27**(16): 2581–2584.

Wang L, Huang RH, Gu L, Chen W, Kang LH. 2009. Interdecadal variations of the East Asian winter monsoon and their association with quasi-stationary planetary wave activity. *Journal of Climate* **22**: 4860–4872, DOI: 10.1175/2009JCLI2973.1.

Wang YF, Owen SM, Li QJ, Peñuelas J. 2007. Monoterpene emissions from rubber trees (*Hevea brasiliensis*) in a changing landscape and climate: chemical speciation and environmental control. *Global Cheng Biology* **13**: 2270–2282, DOI: 10.1111/j.1365-2486.2007.01441.x.

Wang SW, Zhu JH, Cai JN. 2004. Interdecadal variability of temperature and precipitation in China since 1880. *Advances in Atmospheric Sciences* **21**(3): 307–313, DOI: 10.1007/BF02915560.

Wilske B, Cao KF, Schebeske G, Chen JW, Wang A, Kesselmeier J. 2007. Isoprenoid emissions of trees in a tropical rainforest in Xishuangbanna, SW China. *Atmospheric Environment* **41**: 3748–3757, DOI: 10.1016/j.atmosenv.2007.01.008.

Yadav RR, Park W-K, Singh J, Dubey B. 2004. Do the western Himalayas defy global warming? *Geophysical Research Letters* **31**: L17021, DOI: 10.1029/2004GL020201.

Yan Z, Jones PD, Davies TD, Moberg A, Bergström H, Camuffo D, Cocheo C, Maugeri M, Demarée GR, Verhoeve T, Thoen E, Barriendos M, Rodríguez R, Martín-Vide J, Yang C. 2002. Trends of extreme temperatures in Europe and China based on daily observations. *Climatic Change* **53**: 355–392.

Yang Y, Man Z, Zheng J. 2007. Reconstruction of the starting time series of rainy season in Yunnan and the evolvement of summer monsoon during 1711–1982. *Journal Geographical Sciences* **17**(2): 212–220, DOI: 10.1007/s11442-007-0212-9.

Yi Y. 1992. Abrupt warming of global climate in 1980s. *Chinese Science Bulletin* **6**: 528–531.

Yue S, Wang CY. 2004. The Mann-Kendall test modifies by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management* **18**: 201–218.

Zhang J, Zhong Y, Wang D, Zhang X. 2002. Climate change and causes in the Yuanmou dry-hot valley of Yunnan, China. *Journal of Arid Environment* **51**: 153–162.

Zhai P, Sun A, Ren F, Liu X, Gao B, Zhang Q. 1999. Changes of climate extremes in China. *Climatic Change* **42**(1): 203–218.

Zheng X, Kang W, Zhao T, Luo Y, Duan C, Chen J. 2008. Long-term trends in sunshine duration over Yunnan-Guizhou Plateau in Southwest China for 1961–2005. *Geophysical Research Letters* **35**: L15707, DOI: 10.1029/2008GL034482.

