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Temperature and precipitation trends and their links with elevation in the Hengduan Mountain region, China

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ABSTRACT: Annual, seasonal, and monthly changes in temperature and precipitation and their links with elevation in the Hengduan Mountain region (HDMR) in China were analyzed based on the daily climate data of 90 meteorological stations from 1961–2011. The results demonstrate that the average annual mean temperature in the HDMR exhibited significant increasing trends of 0.16°C decade^{-1} during 1961–2011. The warming trends were found to be more apparent in winter (December–January–February) and autumn (September–October–November) than in summer (June–July–August) and spring (March–April–May). All of the 12 monthly mean temperatures increased, with trends ranging from 0.01–0.24°C per 10 yr. Temperatures increased by 0.06°C per 10 yr per 1000 m for elevations ranging from 500–4000 m. The elevation dependency of climatic warming was most robust in winter followed by spring and summer, and was weakest in autumn. The magnitudes of the monthly temperature changes ranged from 0.02–0.10°C per 10 yr per 1000 m. The relationships between annual, seasonal, and monthly temperature trends and elevation indicate evidence of elevation-dependent warming. The average annual total precipitation showed a nonsignificant decreasing trend of −11.41 mm decade^{-1} in the HDMR from 1961–2011. Summer, autumn, and winter precipitation showed nonsignificant decreasing trends during 1961–2011, while spring precipitation exhibited an increasing trend at a rate of 7.34 mm decade^{-1}. The HDMR exhibited a wetting trend during January to May and a drying trend during June to December. The annual and seasonal precipitation changes showed positive correlations with elevation, but annual and seasonal precipitation decreased, except for the spring precipitation (which increased significantly). The relationships between annual and seasonal precipitation trends and elevation indicate that the higher altitude regions experienced a slower drying trend than regions at a lower altitude. The spring precipitation increasing trend was amplified with elevation. This study will be helpful for improving our understanding of the variabilities in temperature and precipitation in response to climate change, and will provide support for water resource management in the HDMR.

KEY WORDS: Temperature · Precipitation trends · Elevation · Hengduan Mountain region · Climate change

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC 2013) Fifth Assessment Report on Climate Change points out that over the past century, almost all regions of the world have experienced a warming process. With an average temperature increase of 0.85°C from 1880 to 2013 (IPCC 2013), many regions are facing dire challenges due to climatic and hydrological situations (Cai et al. 2011, Li et al. 2015). Tem-

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perature and precipitation are 2 of the most important climate elements, and represent a crucial part of the global hydrologic cycle (Thériault et al. 2015). Changes in precipitation and temperature extremes have been observed in many areas (Easterling et al. 2000, Alexander et al. 2006, Ning & Qian 2009). Model outputs show that in the future, extremely high temperature and intense precipitation events will increase, and extreme low temperatures will decrease (Easterling et al. 2000). Extreme climate events are occuring more frequently worldwide in recent decades (Beniston & Stephenson 2004, Zolina et al. 2010, Zhang et al. 2012). Numerous extreme weather and climate events, such as droughts and floods, affect the environment, water resources, and human lives (Easterling et al. 2000, Kunkel 2003, Shi & Xu 2008, You et al. 2010, Boccolari & Malmusi 2013).

Mountain regions provide habitat for many of the world's rare and endangered species (Pepin et al. 2015). In addition, high mountain regions above 2000 m represent the main water supply areas in Asia and are considered 'water towers' of many major river systems (Immerzeel et al. 2010). Mountain areas are more sensitive and vulnerable to climate change than lowlands (S. Wang et al. 2013). Therefore, mountain areas have attracted attention for the study of extreme events in order to identify adaptive actions (Pepin & Lundquist 2008, You et al. 2008, Li et al. 2010, Wang Q et al. 2014, Pepin et al. 2015). Ohmura (2012) showed that temperature variability increased at high altitudes in 10 major mountain regions of the world: the Alps, Kashmir, the Himalayas, Tibet, the Tienshans, the Qilianshans, the Japanese Archipelago, the Andes, the North American Cordillera, and the Appalachians. Dong et al. (2015) investigated the relationship between temperature trends and altitude in China during 1963–2012; they found that temperature trend increased with elevation from 200 to 2000 m. Precipitation in China increased by 2% while the frequency of precipitation events decreased by 10% from 1960–2000 (Liu et al. 2005). At a regional scale, many research studies have analyzed temporal or/and spatial variations in precipitation or/and temperature in many catchments (Liu et al. 2006, Fan et al. 2011, Wang H et al. 2013, Wu et al. 2013, Huang et al. 2014, Wang X et al. 2014). However, most previous studies focused on plains or low-altitude regions, while few studies have been conducted in mountainous areas, especially in high-elevation regions.

The elevation dependency of temperature and precipitation change have attracted attention from both academia and management agencies. Pepin et al. (2015) collected evidence for an amplification of warming rates with elevation, known as elevation-dependent warming (EDW), which means that the temperature changes faster in high-mountain regions than at lower elevations. Li et al. (2012) examined the altitude dependence of trends of daily climate extremes in southwestern China between 1961 and 2008, and the analysis revealed an enhanced sensitivity of climate extremes to elevation in southwestern China in the context of recent warming. Climate models predict that greenhouse warming will cause temperatures to rise faster at higher than at lower altitudes, with implications for glacier mass balance and water resources, montane ecosystems, and higher elevation agricultural activities (Bradley et al. 2004, 2006, Diaz et al. 2014). Liu & Chen (2000) and Liu et al. (2009) also found that the recent warming over the Tibetan Plateau (TP) was correlated with elevation. There is growing evidence for elevation-dependent wetting in the arid region of northwest China, since, with increases in elevation, the water vapour of the mountains shows an increased trend, and increasing water vapour may increase precipitation, so the trends of increasing precipitation are amplified (Yao et al. 2016). The increasing trend in precipitation is relatively prominent at higher elevations, while a decreasing trend is significant at low-elevation stations (Zeng et al. 2016). However, owing to the influence of topography and atmospheric circulation, trend changes in precipitation and temperature due to elevation are complex.

The Hengduan Mountain region (HDMR), located in the southeastern part of the TP, is an area of major runoff production and water resource conservation. Many different ecosystems exist in this region. With an increase in population and economic development, the ecological environment has deteriorated. Changes in land use/land cover and vegetation cover in the HDMR affect thermodynamic activity and further affect the climate and ecological environment of the surrounding areas, even into central and western China (Zhu et al. 2013). Therefore, some scholars have researched the environmental changes in this region. Li et al. (2011) analyzed the spatial and temporal trends of temperature and precipitation in the HDMR. Zhang et al. (2014) analyzed the spatial distribution and temporal trends of extreme precipitation events over the HDMR, and indicated that extreme precipitation events decreased with altitude. However, most studies have concentrated on the spatial and temporal distribution of temperature and precipitation; few have provided insight into the seasonal and monthly changes in temperature and precipitation and the relationship between the trends in temperature and precipitation with regard to elevation in the HDMR. Using meteorological station data, we analyzed changes in annual, seasonal, and monthly temperature and precipitation, and investigated the relationship between temperature and precipitation trends with regard to elevation. The findings will be helpful for improving our understanding of the temperature and precipitation responses to climate change in the HDMR, and for providing support for water resource management in this region.

2. STUDY AREA, DATA, AND METHODS

2.1. Study area

The HDMR is located in the southeastern part of the TP (24°40′–34°00′ N, 96°20′–104°30′ E) and comprises an area of 449698 km^2 (Fig. 1). There are numerous mountains (e.g. Mt. Minshan, Mt. Qionglaishan, Mt. Daxueshan, Mt. Shalulishan, Mt. Habaxueshan, Mt. Yulong, Mt. Ningjingshan, Mt. Yunling, Mt. Gaoligongshan) and rivers (e.g. the Mijing, Daduhe, Ya-lung, Chin-sha, Lancang, and Nujiang Rivers) in the HDMR. Elevations range from above 5000 m in the north to >4000 m in the south. The highest peak is Mt. Gonggashan (7556 m), located in the central HDMR. The elevation decreases from the northwest to the southeast (Fig. 1). All rivers in the HDMR drain into the Pacific Ocean except the Nujiang River, which drains into the Indian Ocean from the southwestern part of the HDMR. The HDMR has a typical monsoonal climate that is controlled by the East and South Asia monsoons (May–October), the TP monsoon, and the westerlies (Li et al. 2012). Owing to the effect of the complex topography, the HDMR has extreme vertical climate zones. The monsoon brings a large amount of moisture, with rain accounting for 75–90% of total annual precipitation. November to April is the winter monsoon period, which is influenced by the TP monsoon and the westerlies. Influenced by the monsoons' strength or weakness, this region has experienced extreme flood or drought events, such as the severe drought in southwest China from autumn 2009 to spring 2010 (Zhou et al. 2009, Lu et al. 2011).

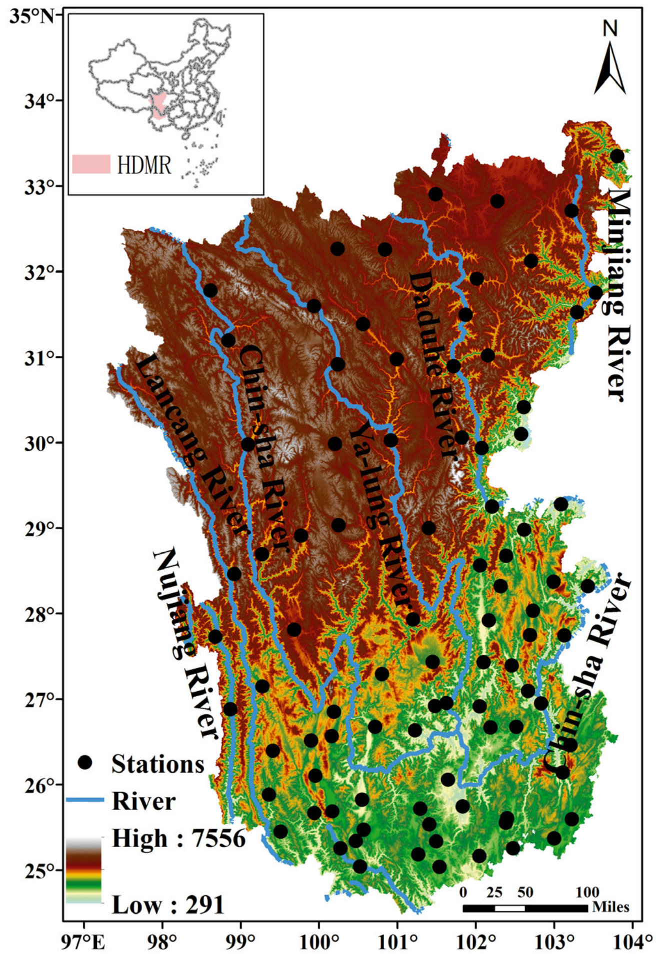


Fig. 1. Digital elevation model of the Hengduan Mountain region (HDMR) and locations of the meteorological stations

2.2. Data and methods

Daily temperature and precipitation data were obtained from the National Meteorological Information Center of the China Meteorological Administration (CMA) (http://data.cma.cn/site/index.html). The data lacked uniformity because the beginning of the recording dates was inconsistent, and some stations had missing data. Based on accepted standards that the observed data should be continuous and as long as possible in duration, we chose 1961 as the start year, and used stations without missing data. After rejecting 8 stations with inconsistent data series, 90 stations were finally selected for this study (Fig. 1). The weather station data ranged from 1 January 1961 to 31 December 2011. The elevations of the selected stations ranged from 639.5 m (Ebian station) to 3948.9 m (Litang station); a histogram of the elevations of the 90 stations is shown in Fig. 2. There were only 4 stations below 1000 m, 44 stations between 1000 and 2000 m, 42 stations above 2000 m, and 12 stations above 3000 m; no station has an elevation higher than 4000 m in the HDMR.

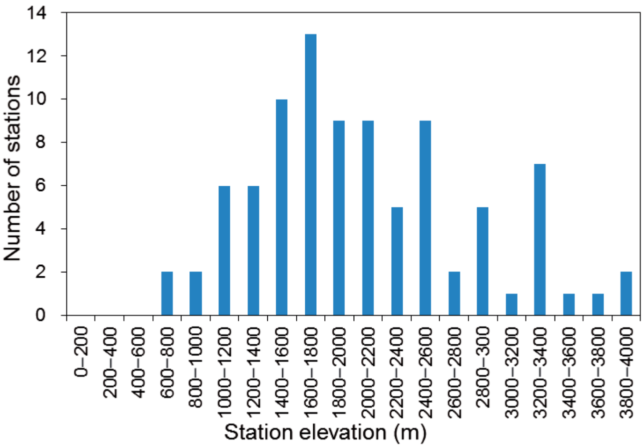


Fig. 2. Elevations of the meteorological stations in the Hengduan Mountain region

We used linear regression to study temperature and precipitation trends and the relationship between these trends and elevation. The trends in temperature and precipitation were investigated for different elevations in different periods, seasons, and months. In this study, March–May, June–August, September–November, and December–February represent spring, summer, autumn, and winter, respectively. The Mann-Kendall nonparametric statistical test (Yue et al. 2002) was used to detect trends in the time series of temperature and precipitation in the HDMR and to determine the correlation coefficients between the trends in temperature and precipitation and elevation.

3. RESULTS

3.1. Temperature and precipitation trend characteristics

Fig. 3 shows the distribution of the trends of annual mean temperature (T_{ann}) and annual total precipitation (P_{ann}) in the HDMR during 1961–2011. T_{ann} increased by 0.16°C decade^{-1} in the HDMR, which indicates a significant warming trend at the 0.01 significance level based on results calculated by the Mann-Kendall method. A significant warming trend was observed; only 8 stations in the south HDMR experienced a cooling trend and 2 stations had values at the 0.05 significance level (Fig. 3a, Table 1); 82 of the 90 stations (accounting for 91%) showed a

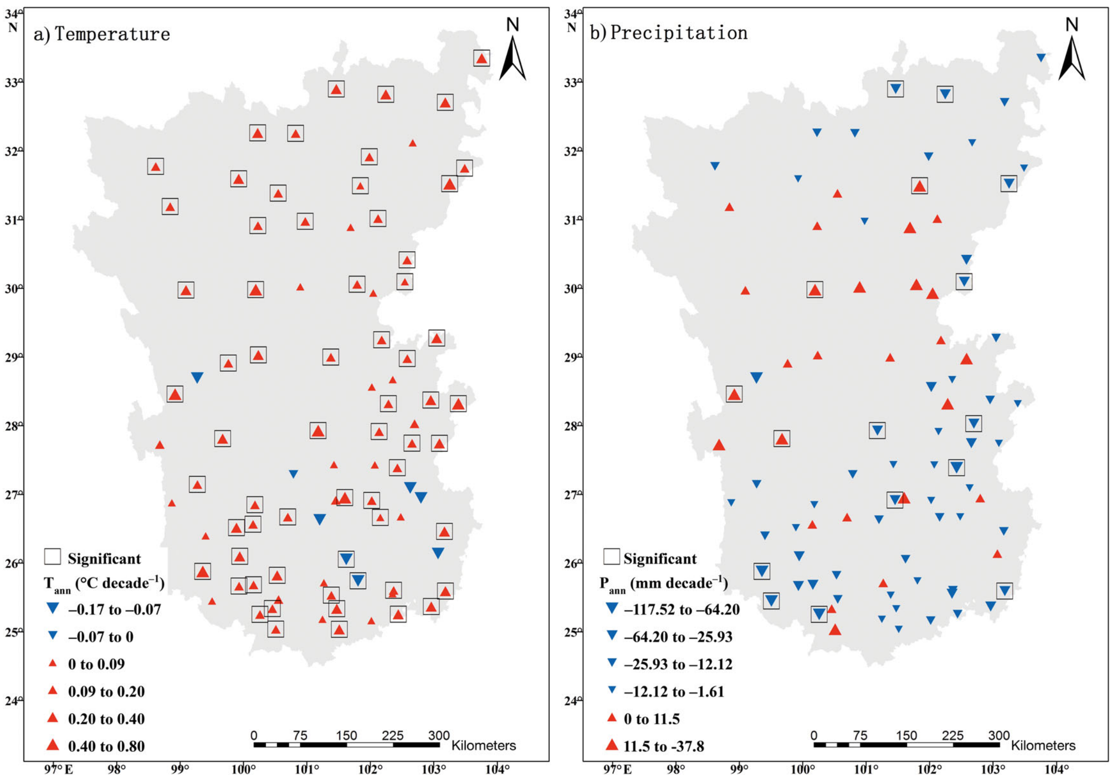


Fig. 3. Distribution of the annual mean (a) temperature (T_{ann}) and (b) precipitation (P_{ann}) trends in the Hengduan Mountain region during 1961–2011 (statistical significance at 0.05 level)

warming trend and 68.9% reached the 0.05 significance level. P_{ann} decreased by −11.41 mm decade^{-1} in the HDMR, indicating a drying trend, while no significant long-term linear trend was observed. The northeast and south of the HDMR became dryer; however, wetting occurred in the middle and north regions of the HDMR (Fig. 3b). The statistical results showed that 68.9% of the stations became dryer, while only 13.3% reached the 0.05 significance level (Table 1). These results indicate a clear warming trend and a non-significant drying trend in the HDMR during 1961−2011. Temperature increases for spring, summer, autumn, and winter were 0.09°C per 10 yr ($p = 0.0911$), 0.14°C per 10 yr ($p = 0.0002$), 0.16°C per 10 yr ($p = 0.0009$), and 0.27°C per 10 yr ($p < 0.0001$), respectively (Fig. 4). A significant warming trend was observed for all 4 seasons, except spring. The most significant warming trend occurred in winter, followed by autumn, summer, and spring. In the winter, 84 stations exhibited warming; furthermore, 70 stations reached the 0.05 significance level, while only 6 stations showed a cooling trend, which was not significant (Table 1). There were 63 stations exhibiting a warming trend in the spring (32.2% reached the 0.05 significance level) and 27 stations exhibiting a cooling trend (6.7% reached the 0.05 significance level); this resulted in a nonsignificant warming trend for the mean temperature in spring. The distribution of the seasonal precipitation trend in the HDMR during 1961−2011 is shown in Fig. 5. The precipitation trends in spring, summer, autumn, and winter were 7.34 mm per 10 yr ($p = 0.0116$), −7.87 mm per 10 yr ($p = 0.1281$), −8.90 mm per 10 yr ($p = 0.0160$), and −2.07 mm per 10 yr ($p = 0.0378$), respectively. The precipitation in the spring increased significantly, while precipitation in the other seasons decreased, and autumn and winter precipitation were statistically significant at the 0.05 level. The most significant drying trend was observed in autumn, followed by summer and winter, while spring precipitation increased significantly. In the spring, 93.3% of stations exhibited a precipitation increase (38.9% reached the 0.05 significance level; Table 1) and 76.7% of the stations exhibited drying trends for precipitation in the summer, especially in the northeast and southwest of the HDMR (Fig. 5b, Table 1). Overall, 78.9% of the stations exhibited drying trends for precipitation in autumn, mainly concentrated in the north and south of the study region (Fig. 5c, Table 1). Winter precipitation showed little change at a rate of −2.07 mm per 10 yr in the past 51 yr and 56.7% of the stations exhibited drying trends, especially in the south of the HDMR (Fig. 5d, Table 1). Because the precipitation was mainly concentrated in the summer (accounting for 54.4% of P_{ann}), the precipitation decrease was nonsignificant in the summer; although autumn and winter precipitation decreased significantly, spring precipitation increased significantly, and this led to a nonsignificant decrease in P_{ann}. The trends for temperature and precipitation indicated that the regions experienced warming and drying trends for the period of 1961−2011.

In order to examine the trends of temperature and precipitation in more detail, we calculated the trends in monthly mean temperatures and total precipitation amounts in the HDMR during 1961−2011 (Fig. 6). We also determined the percentage of stations with significant and nonsignificant trends (positive or negative) (Fig. 7). All 12 monthly mean temperatures exhibited an increasing trend, ranging from 0.01−0.24°C per 10 yr (Fig. 6a), and the trends were significant at the 0.05 level in January, June, August, September, November, and December. The increasing trend in monthly mean temperature was largest in January, followed by June, November, and December; all 4 of these monthly mean temperatures were above 0.20°C per 10 yr. The trends for May and

Table 1. Numbers of stations and temperature and precipitation trends on an annual and seasonal basis in the Hengduan Mountain region. Parentheses: no. of sites that passed the 0.05 significance level test

Time period	Temperature				Precipitation			
	Warming		Cooling		Wetting		Drying	
	Number	Trend (°C decade^{-1})	Number	Trend (°C decade^{-1})	Number	Trend (mm decade^{-1})	Number	Trend (mm decade^{-1})
Annual	82(62)	0.19	8(2)	−0.09	28(4)	14.52	62(12)	−23.13
Spring	63(29)	0.18	27(6)	−0.10	84(35)	8.26	6(0)	−5.59
Summer	78(55)	0.17	12(0)	−0.04	21(1)	8.58	69(14)	−12.73
Autumn	81(51)	0.19	9(0)	−0.06	19(0)	4.58	71(21)	−11.99
Winter	84(70)	0.30	6(0)	−0.11	39(4)	1.51	51(14)	−4.80

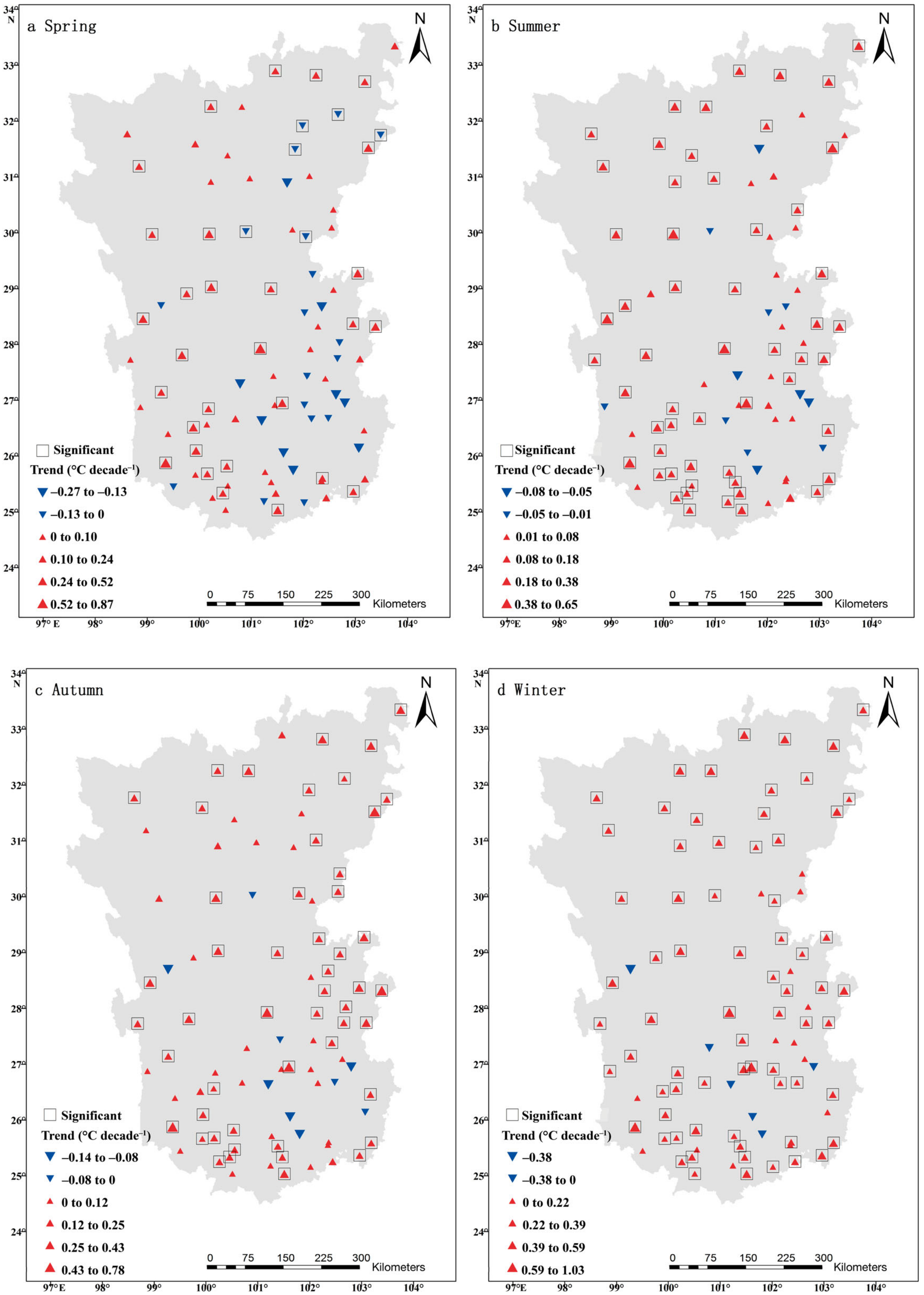


Fig. 4. Distribution of the seasonal mean temperature trend in the Hengduan Mountain region during (a) spring, (b), summer, (c) autumn, and (d) winter of 1961–2011 (statistical significance at 0.05 levels)

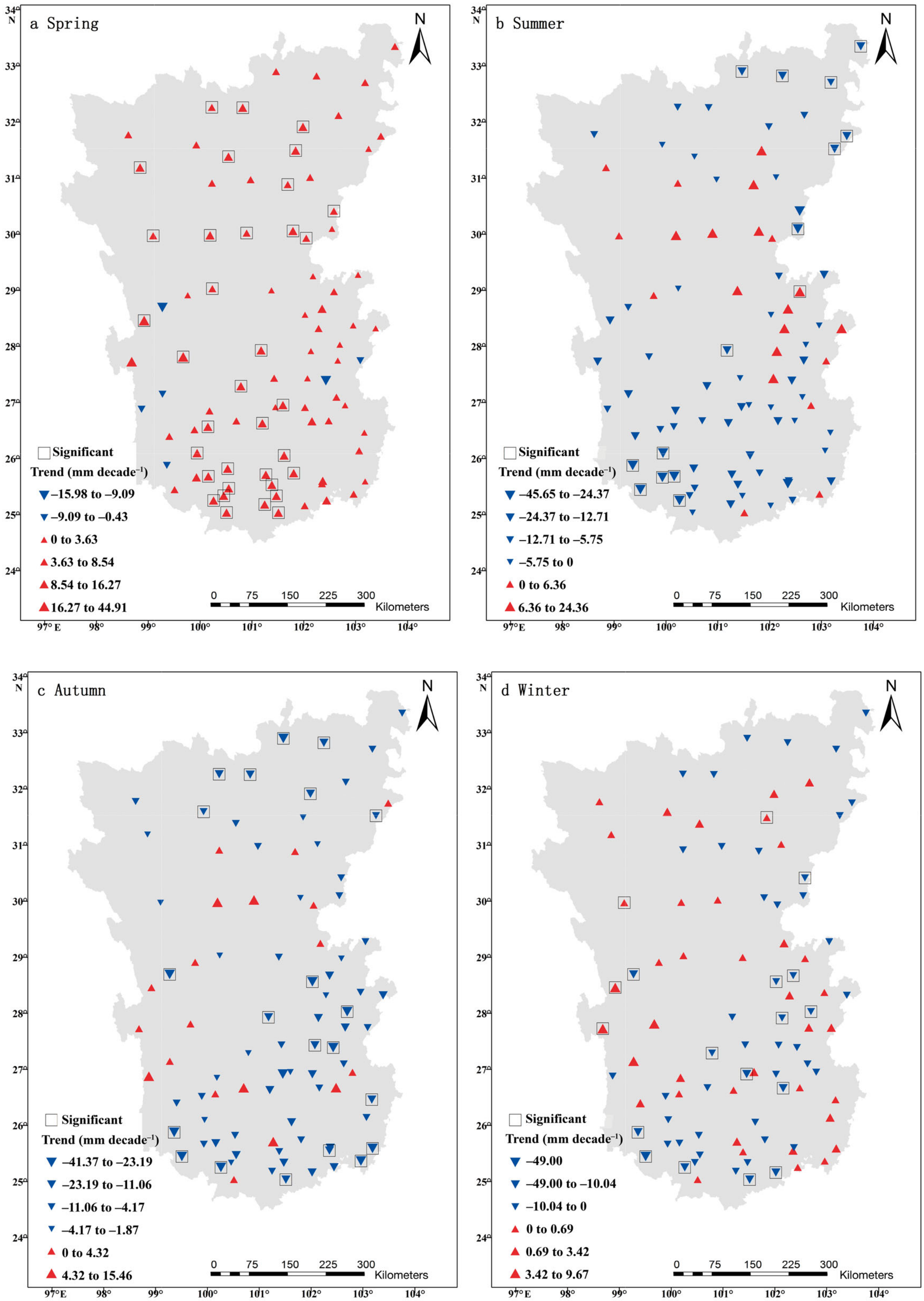


Fig. 5. Distribution of the seasonal precipitation trend in the Hengduan Mountain region during (a) spring, (b), summer, (c) autumn, and (d) winter of 1961–2011 (statistical significance at 0.05 levels)

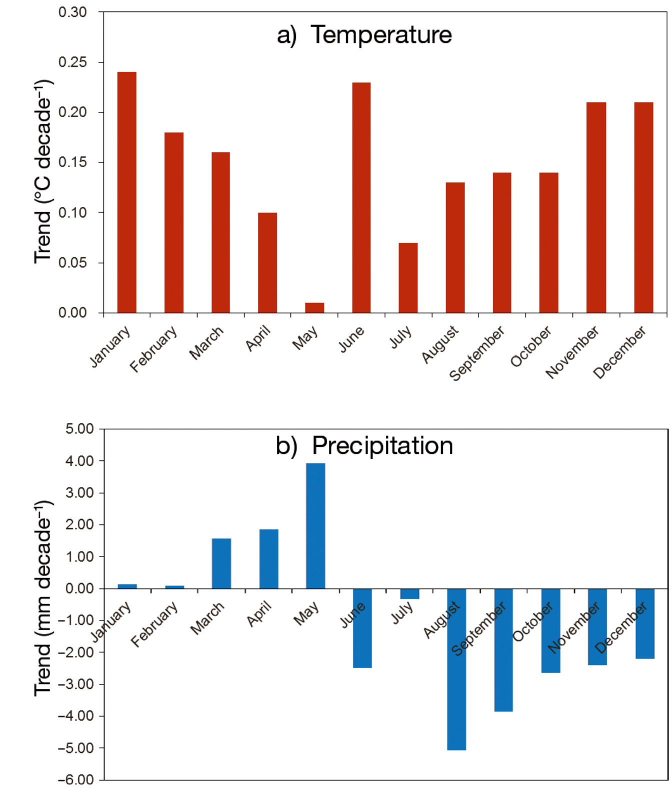


Fig. 6. Monthly (a) temperature and (b) precipitation trends in the Hengduan Mountain region during 1961–2011

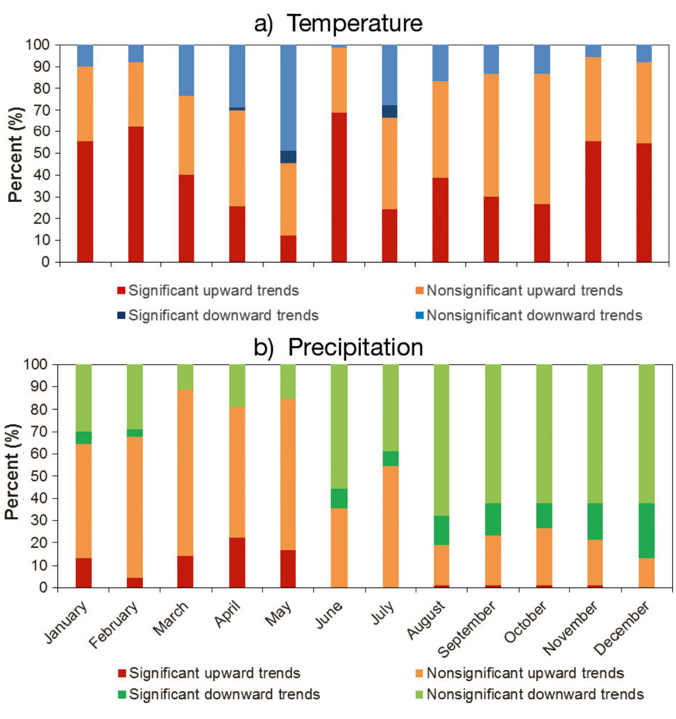


Fig. 7. Percent of stations with different significant levels for the monthly (a) temperature and (b) precipitation trends in the Hengduan Mountain region during 1961–2011

July were 0.01 and 0.07°C per 10 yr, respectively, and the other monthly mean temperature trends were between 0.10 and 0.20°C per 10 yr. Less than 50% of the stations showed warming trends for May, while the other months were above 66.7% (Fig. 7a); the percentages for January, February, June, November, and December were above 90%.

Trends in precipitation were above zero from January to May and below zero from June to December (Fig. 6b); the data indicate a wetting trend during January–May and a drying trend during June–December. Only the trends of November and December reached the 0.05 significance level. The precipitation in May had the largest wetting trend magnitudes (3.92 mm per 10 yr) and the precipitation in August had the largest drying trend magnitudes (−5.06 mm per 10 yr). Although the percent of the upward trends ranged from 64–89% from January–May, there were fewer stations (4–22%) that showed a significant upward trend for precipitation. In contrast, the percent of the downward trend from June to December ranged from 46–87% and fewer stations (7–24%) showed a significant downward trend. These results illustrate that the precipitation decrease was nonsignificant.

3.2. Relationship between temperature trend and elevation

The relationship between the annual and seasonal temperature trends and altitude were analyzed using linear regression (Fig. 8). T_{ann} increased by 0.06°C decade^{-1} per 1000 m (R^2 = 0.083, $p < 0.05$) for altitudes ranging from 500–4000 m, showing an increasing trend with an increase in elevation during 1961–2011 (Fig. 8a). The warming trends increased with increasing altitude annually and for all seasons in the HDMR (Fig. 8). The elevation dependency of the climatic warming was most robust in winter, followed by spring, summer, and autumn. The rates of increase in winter, spring, summer, and autumn were 0.10, 0.08, 0.07, and 0.03°C per 10 yr per 1000 m. Furthermore, all rates of increase were significant at the 0.05 significance level, except for autumn (p = 0.2074; Fig. 8d), indicating that the influence of altitude on temperature was marked except in autumn. Fig. 4c shows that the temperature in autumn exhibits significant increasing trends in the east and south of the HDMR, although the temperature in the west also shows an increasing trend but is not significant. The topography declines from west to east and north to east for the HDMR (Fig. 1). The results show

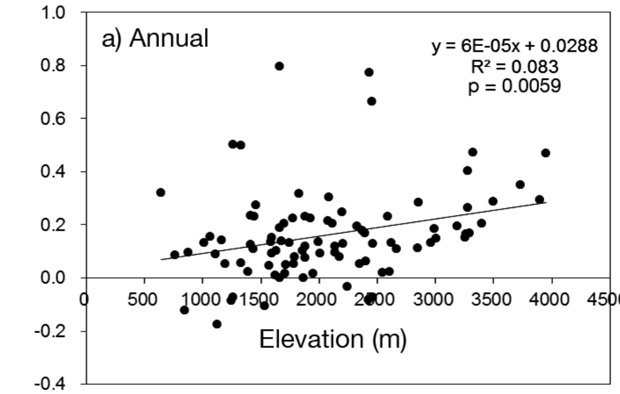
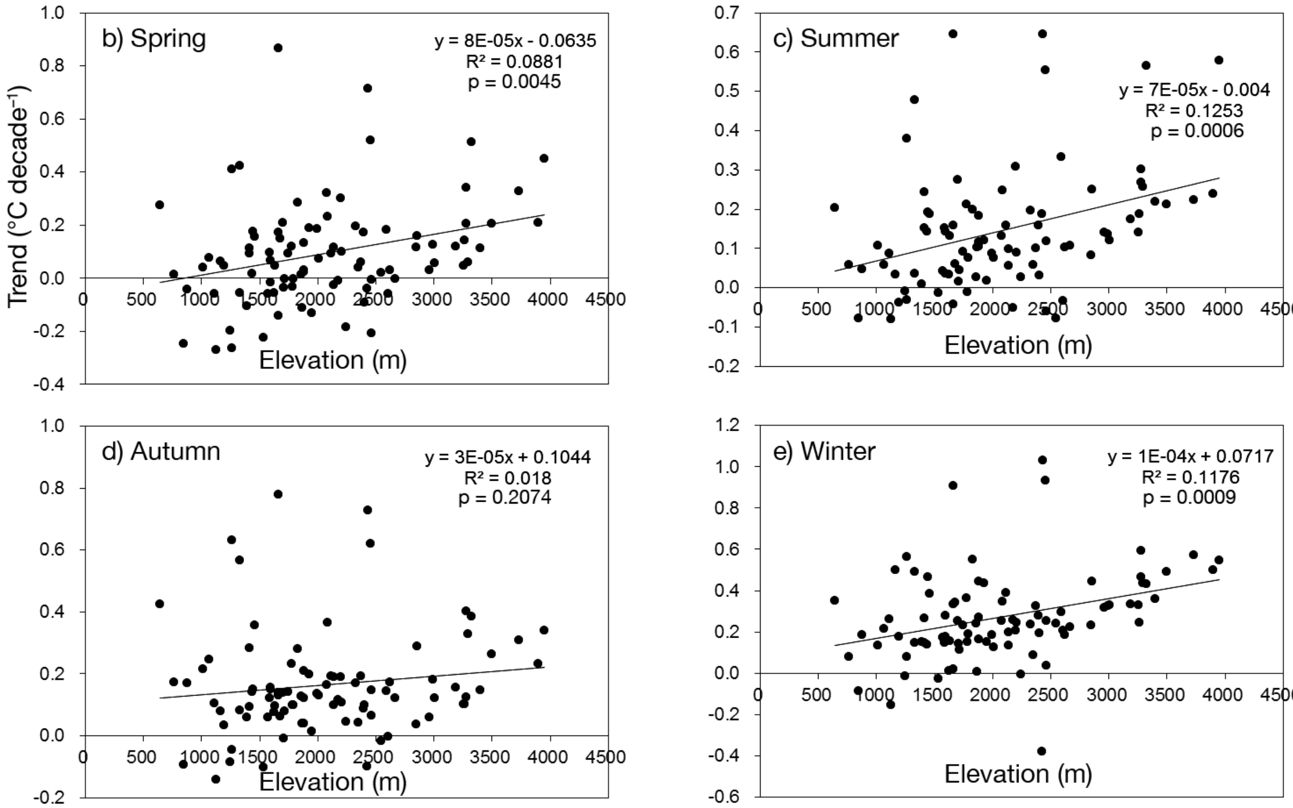


Fig. 8. Trend magnitudes of (a) annual and (b–e) seasonal mean temperature versus elevation in the Hengduan Mountain region. R^2: correlation coefficients for the relationships; p: statistical significance



that there was no significant correlation between the autumn trends in temperature and elevation.

Fig. 9 further shows the relationships between the magnitudes of the trends for the monthly temperatures and elevation. There were positive correlations between temperature and elevation trend for all 12 months, and the relationships were significant except for February, September, October, and November (Fig. 9). The positive relationships had the largest magnitudes in January and December (both were 0.10°C per 10 yr per 1000 m). In contrast, the magnitudes were lowest for September, October, and November (0.04, 0.02, and 0.03°C per 10 yr per 1000 m, respectively). These results further demonstrate that the elevation dependency of climatic warming was weakest in autumn. The relationships between annual, seasonal, and monthly temperature trends and elevation indicated that higher altitude areas experienced more warming than areas at lower elevations.

3.3. Relationship between precipitation trend and elevation

Similar to the temperature–elevation analysis, the relationship between annual, seasonal, and monthly precipitation trends and altitude were analyzed

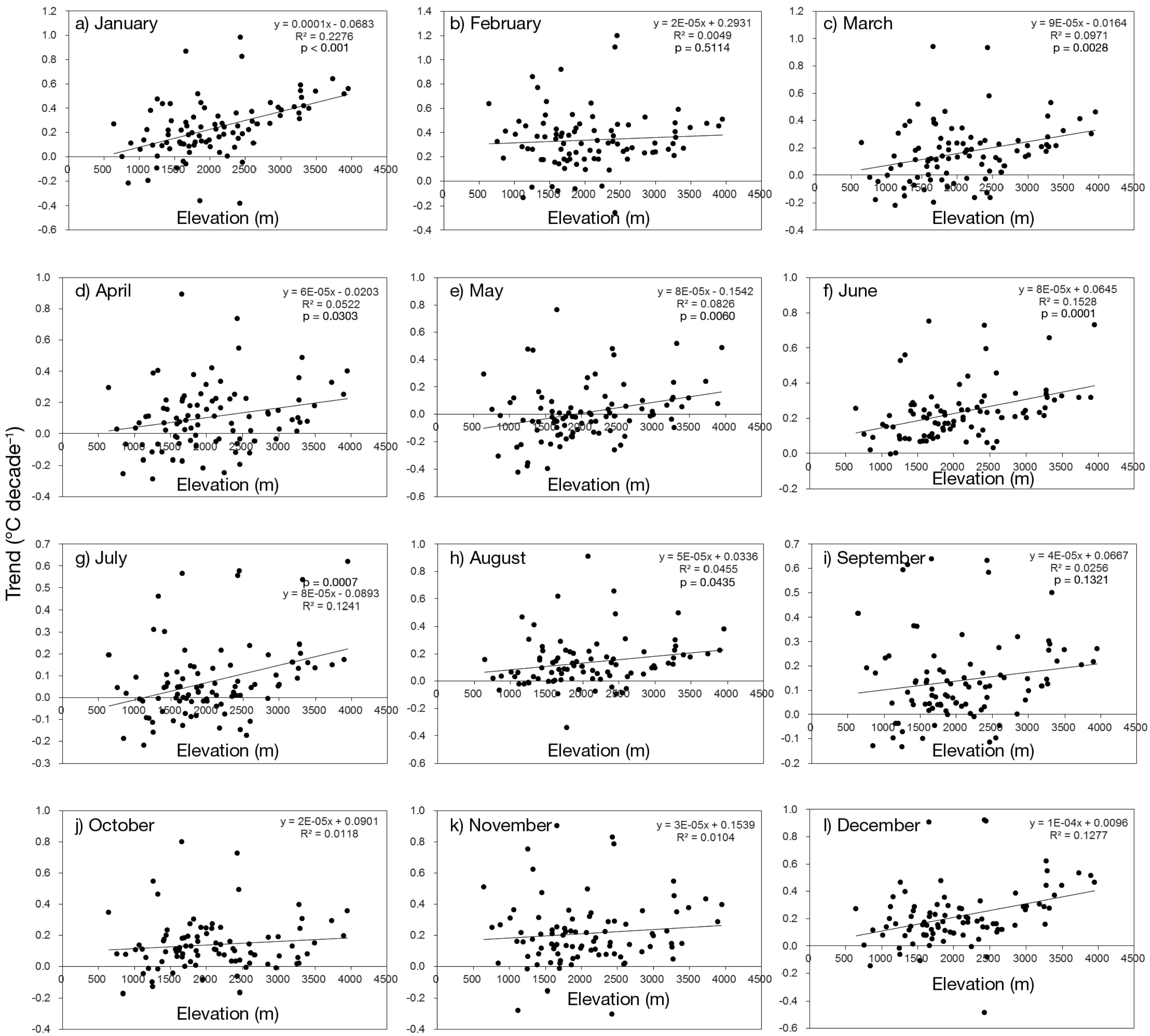


Fig. 9. Trend magnitudes of monthly mean temperature versus elevation in the Hengduan Mountain region. R^2: correlation coefficients for the relationships; p: statistical significance

using linear regression (see Figs. 10 & 11). Precipitation increased by 7.8 mm decade^{-1} per 1000 m (R^2 = 0.0525, $p < 0.05$) for altitudes ranging from 500–4000 m, showing an increasing trend with an increase in elevation during 1961–2011 (Fig. 10a). P_{ann} decreased by −11.41 mm decade^{-1} in the HDMR, which showed a nonsignificant drying trend. That is to say, the drying trend was slower at higher elevations. The elevation dependence of precipitation was robust in summer, followed by winter and spring, and was weakest in autumn; the rates of change in the summer, winter, spring, and autumn were 3.1, 2.0, 1.7, and 1.0 mm per 10 yr per 1000 m, and only the value for the winter reached the 0.05 significance level ($p = 0.0492$; Fig. 10e). This indicates that the influence of elevation on seasonal precipitation was not marked except during winter. Fig. 5d shows that winter precipitation exhibited a drying trend in the south and an increasing trend in the northwest of the HDMR. Therefore, there was a positive correlation between the winter trends in precipitation and elevation.

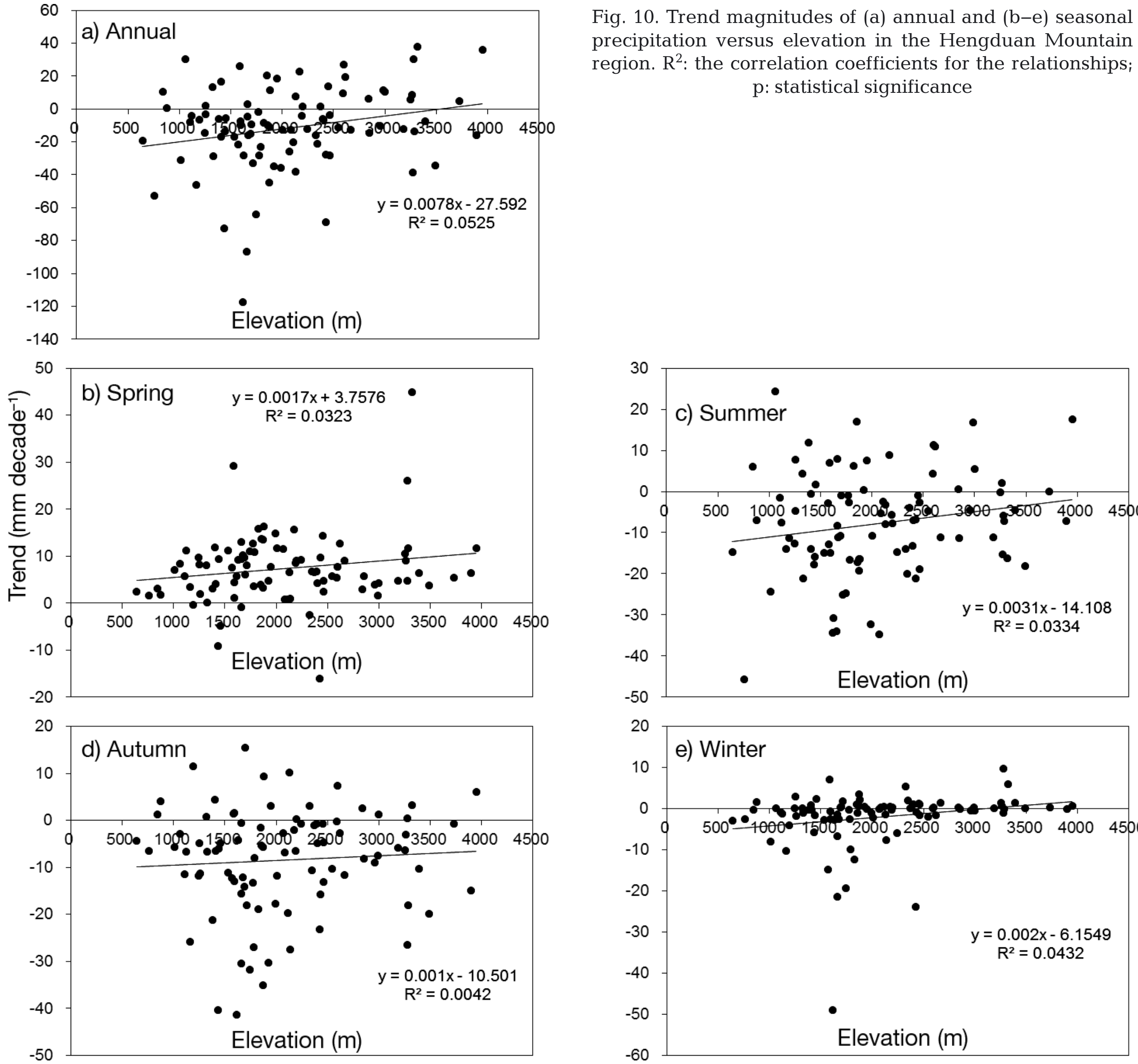


Fig. 10. Trend magnitudes of (a) annual and (b–e) seasonal precipitation versus elevation in the Hengduan Mountain region. R^2: the correlation coefficients for the relationships; p: statistical significance

Fig. 11 further reveals the relationships between the magnitudes of the trends for monthly precipitation and elevation. April, August, and December precipitation trends showed positive and significant correlations with altitude (2.3, 1.2, and 1.1 mm per 10 yr per 1000 m, respectively). May, July, and September precipitation trends showed negative and nonsignificant correlations with altitude, with trend magnitudes of −0.1, −0.2, and −0.03 mm per 10 yr per 1000 m, respectively. The relationship between the other monthly precipitation trends and elevation were positive and nonsignificant, ranging from 0.2 to 1.0 mm per 10 yr per 1000 m (Fig. 11).

Although the annual and seasonal precipitation trends showed positive correlations with elevation, P_{ann} and seasonal precipitation decreased except for spring precipitation (which increased significantly) in the HDMR during 1961–2011. The relationships between annual and seasonal precipitation (except for spring precipitation) trends and elevation indicated that the higher altitude regions experienced a slower drying trend than regions at lower altitudes. The spring precipitation wetting trend was amplified with elevation. Except for May, July, and September, when the precipitation trends showed negative correlations with elevation, the

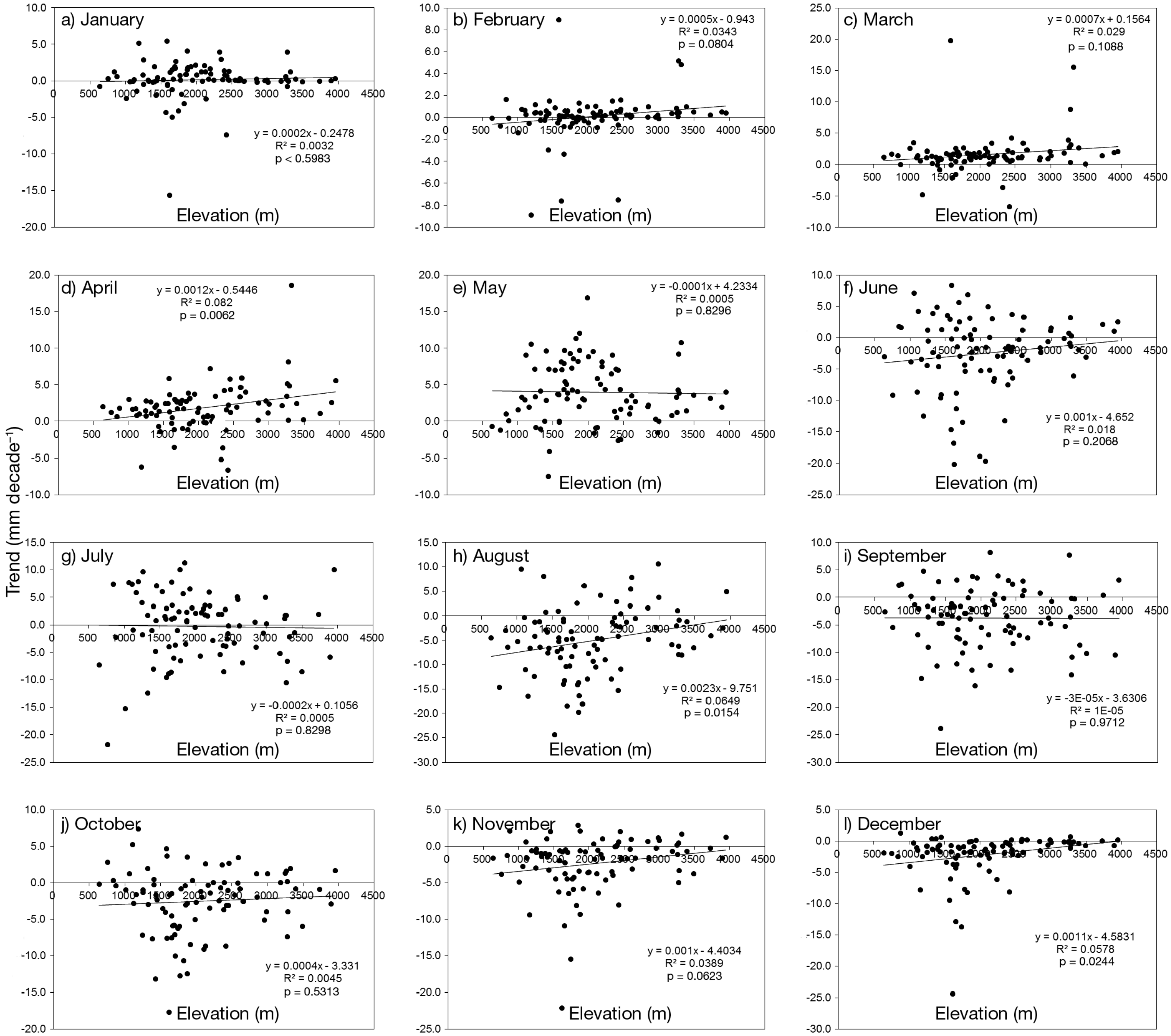


Fig. 11. Trend magnitudes of monthly precipitation versus elevation in the Hengduan Mountain region. R^2: correlation coefficients for the relationships; p: statistical significance

other monthly precipitation trends showed positive correlations with altitude. Additionally, monthly precipitation from January to May showed non-significant increasing trends while precipitation in the other months showed drying trends. Therefore, the relationships between the January, February, March, and April precipitation wetting trends were amplified with elevation. Compared with the relationship between temperature and elevation, the relationship between precipitation and elevation is much more complex.

4. DISCUSSION

4.1. Temperature and precipitation trends in the HDMR

The HDMR showed a significant warming trend, with a rate of 0.16°C decade^{-1} during 1961–2011 and 0.38°C decade^{-1} during 2001–2011. The result of the increasing trend in T_{ann} is similar to the findings of a previous study of the HDMR that showed an increasing trend of 0.15°C decade^{-1} during 1960–2008 (Li et al. 2011), and is slightly lower than the results (0.173°C decade^{-1}) conducted in Sichuan Province for the period of 1960–2009 (S. Wang et al. 2013). Our result is significantly lower than that of a study at the national level that showed an increase of 0.26°C decade^{-1} during 1963–2012 (Dong et al. 2015) and 0.30°C decade^{-1} in the Yunnan Plateau during 1961–2004 (Fan et al. 2011). Furthermore, the stronger warming during the most recent 11 yr is consistent with the results reported for the TP (Dong et al. 2015) and for a previous study of the HDMR (Li et al. 2011). There were 8 stations with a decreasing trend in T_{ann} in the southeast of the HDMR during 1961–2011 (Fig. 3a). Previous studies in this region also found a cooling trend (Zhang et al. 2002, Qin et al. 2010, Fan et al. 2011). Some researchers showed that the decrease in temperature was due to increasing atmospheric aerosol concentrations from regional pollutants in the Sichuan basin and vicinity, which decreased the intensity and duration of sunshine, resulting in a decrease in temperature (Qian & Giorgi 2000, Li et al. 2011). At the seasonal scale, the increase in magnitude of the mean temperature is most notable in winter, followed by autumn and summer, and is weakest in spring. This indicates that the increased magnitude of T_{ann} can be mainly attributed to the warming contribution in winter and autumn. The warming magnitude was higher in the middle and north regions than in the south of the HDMR during 1961–2011.The changes in the P_{ann} showed a regional and seasonal difference in the HDMR. P_{ann} decreased by −11.41 mm decade^{-1} during 1961–2011, which is different from the results of a previous study in the HDMR where the precipitation increased 9.09 mm decade^{-1} during 1960–2008 (Li et al. 2011). However, in that study, the number of stations and the elevation ranges of the stations were different. We selected 90 stations with elevations ranging from 639.5–3948.9 m, while only 27 stations were used in their study with elevations ranging from 1244.8–4200 m. The study periods were different as well; our study period was 1961–2011 while the other study used 1960–2008. Furthermore, it is well known that southwestern China experienced the worst water shortage in 100 yr from autumn 2009 to spring 2010. In addition, our results indicate that precipitation exhibited an increasing trend at a rate of 1.22 mm decade^{-1} during 1961–2000 in the HDMR, and southwest China has experienced an ongoing drought since 2000 (Wu et al. 2013). All of these differences may be the main cause for the differing results between the 2 studies (Li et al. 2011). In addition, P_{ann} showed nonsignificant decreasing trends of −4.19 mm decade^{-1} in Sichuan Province during 1960–2009 (Wang S et al. 2013), and increasing trends of 0.61 mm yr^{-1} in northwest China during 1960–2010 (Li et al. 2016). At a seasonal scale, P_{ann} decreased in all seasons except spring. The drying was most notable in autumn, followed by summer and winter during 1961–2011. The precipitation decreased at rates of −8.90, −7.87, and −2.07 mm decade^{-1} in autumn, summer and winter, respectively, while it increased by 7.34 mm decade^{-1} in spring. The significant increase in spring precipitation was consistent with the results of previous studies (You et al. 2012, Tong et al. 2014). The P_{ann} decrease may have been caused by the decrease in autumn and summer, which are the flood seasons in the HDMR. The results of the temperature and precipitation trends in the HDMR indicated that this region experienced warming and drying during 1961–2011, especially during the period of 2001–2011.

Temperature and precipitation are affected by atmospheric circulation and human activities. The HDMR is located in a typical monsoonal climate region and is affected by the TP monsoon and the westerlies in spring and winter, the South China Sea and the Bay of Bengal monsoons in summer, and the western Pacific monsoon in autumn. Summer and autumn are the main periods of rainfall in the HDMR. The decrease in water vapor from the Bay of Bengal and the South China Sea and Western Pacific during summer and autumn is the main reason for the significant drying trend in the HDMR during 1961–2011 (Zhou et al. 2009, Gong & He 2002). When the western Indian Ocean's sea surface temperatures are warmer, the easterly wind appears in the tropical Indian Ocean and a cyclonic anomalous circulation occurs in the western Indian Ocean. The warm and moist airflow in the western Indian Ocean enters mainland China along the west side of the TP, moves around the TP from north to south, and finally enters the Bay of Bengal, which limits the development of a trough over the Bay of Bengal; therefore, water vapor transport to the HDMR is decreased, resulting in less precipitation (Tan et al. 2015). Under this abnormal circulation, it is sunny with little rain in HDMR, and the high temperatures result in continuous drought (Xu et al. 2014). Because of the abnormality of the atmospheric circulation and the continuous strengthening of the Arctic Oscillation, the East Asian monsoon (EAM) weakened in the winter (Ju et al. 2004). The East Asia major trough was weak, the cold air restricted the movement and held the abnormal circulation over the South China Sea, resulting in a weakening of the warm moist air flows in the HDMR.

All of this has contributed to the warming in the winter in the HDMR. The WPSH is strong and moves westward, resulting in a warming and drying trend in the autumn in the HDMR. Studies have indicated that the water vapor originating from the South China Sea and the Bay of Bengal monsoon, moving into the southwest, decreased in the summer; on the other hand, water vapor from the westerlies increased (Zhou et al. 2009, Li et al. 2012). Therefore, summer precipitation exhibited a non-significant decrease under the combined effects of the summer monsoon and the westerlies. However, due to the increases in the westerlies, spring precipitation increased significantly. Summer is the main rainfall season with 60–70% of the P_{ann}. The decrease in summer precipitation was not significant, and although autumn and winter showed significant drying trends, the spring precipitation increased significantly. This caused a nonsignificant decreasing trend in P_{ann} of −11.41 mm decade^{-1} in the HDMR.

The temperature increased significantly and precipitation decreased non-significantly in the HDMR during 1961–2011. The South Asian Summer Monsoon (SAM) and the EAM are important influences on precipitation in the HDMR (Zhang et al. 2014). The SAM and EAM decreased, while the WPSH was strong and moved westward in recent years, resulting in warming and drying trends in the southwest in the 21st century (Li et al. 2012). Increases in anthropogenic aerosols led to a weakening of the EAM and a decrease in precipitation in China (Menon et al. 2002, Liu et al. 2011, T. Wang et al. 2015, H. Wang et al. 2015, Xie et al. 2016). The effects of socio-economic development in the HDMR, especially the Chinese Western Great Development after 2000, resulted in more aerosol emissions, and the drying trend was most robust during 2001–2011.

4.2. Elevation dependency of the trends in temperature and precipitation

Climate change in higher altitude regions has received increased attention and there is growing evidence that the rate of warming is amplified with elevation. The relationships between annual, seasonal, and monthly temperature trends and elevation indicated that higher altitude areas experienced more warming than areas at lower elevations. For example, T_{ann} increased by 0.06°C decade^{-1} per 1000 m in the elevation range from 500–4000 m, and the winter temperature trend increased by 0.10°C decade^{-1} per 1000 m, which was the most robust trend amongst the seasons. These results indicate that the high mountain regions experienced more rapid changes in temperature than regions at lower elevations. This is consistent with previous studies (Giorgi et al. 1997, Beniston 2003, Liu et al. 2009, Li et al. 2011, 2012, Yan & Liu 2014, Dong et al. 2015, Yan et al. 2016). There are a series of mechanisms that contribute to the amplification of warming with elevation, such as snow/ice albedo feedbacks, water vapor, clouds, and aerosols.

As a result of climate warming, the amount of surface snow/ice in high-altitude areas is being reduced. The decrease in snow/ice leads to a decrease in surface albedo, and the increasing solar radiation is absorbed by the earth's surface, resulting in higher temperatures and further reduction of the surface snow/ice mass. This feedback process increases the temperatures at higher altitudes. The HDMR is one of the main distribution areas of the monsoonal temperate glaciers in China, and glaciers are decreasing and snowlines are retreating under climate warming (Li et al. 2011). Climate warming and decreases in glacial snow cover affect one another. On the one hand, climate warming leads to the reduction of glaciers and snowpack. On the other hand, the reduction of glaciers and snowpack causes high altitude areas to heat up. This is the main reason for the EDW in the winter and spring in the HDMR.

Increases in water vapor in the air can lead to an increase in downward longwave radiation (DLR), but the relationship between water vapor and DLR is non-linear (Ruckstuhl et al. 2007). A small increase in water vapor in the air causes a significant increase in the DLR, resulting in accelerated heating. Winter and spring are dry, with robust warming trends, and the increases in the westerlies resulted in increases in the water vapor in the HDMR in winter and spring; this also contributed to EDW. Both observations (Rangwala 2013) and climate models (Rangwala et al. 2009) have suggested that water vapor contributes to EDW.

Changes in clouds affect both shortwave and longwave radiation and thus the surface energy budget (Pepin et al. 2015). There are fewer clouds at lower altitudes and more clouds at higher altitudes, resulting in less shortwave radiation absorbed at lower altitudes and greater DLR; at the same time, the surface solar and infrared radiation increase, which has a net effect of warming at high elevation, causing EDW. Based on the simulation results of high spatial resolution models, Liu et al. (2009) also suggested that the cloud-radiation effect was one of the main mechanisms of EDW in the southeast TP.

Aerosols absorb solar and infrared radiation and reduce surface albedo when deposited on snow, resulting in lower amounts of sunlight reaching the ground which causes local cooling. Most of the aerosols are concentrated at relatively low elevations (below 3 km) (Ramanathan & Carmichael 2008); as a result, the effects of solar shortwave radiation are reduced at lower elevations, while the impact on solar radiation in high-altitude areas is small; thus higher elevation areas exhibit higher warming trends. T_{ann} increased by 0.03°C decade^{-1} per 1000 m in the elevation range of 500–3000 m (Fig. 12a) and by 0.20°C decade^{-1} per 1000 m in the elevation range of 3000–4000 m (Fig. 12b). This demonstrates that aerosols have more impact on temperatures in low-elevation regions than in high-elevation regions.

The annual and seasonal precipitation trends showed positive correlations with elevation. For example, P_{ann} increased by 7.8 mm decade^{-1} per 1000 m for altitudes ranging from 500–4000 m, showing an increasing trend with an increase in elevation during 1961–2011 (Fig. 10a). It is worth noting that P_{ann} showed a nonsignificant drying trend of −11.41 mm decade^{-1} in the HDMR during 1961–2011. That is to say, the drying trend was slower at higher than at lower elevations. A significant wetting trend of 7.34 mm decade^{-1} was observed in the spring and the elevation dependence of precipitation was 1.7 mm per 10 yr per 1000 m (not significant at the 0.05 significant level); the spring precipitation wetting trend was amplified with elevation. There is growing evidence of elevation-dependent wetting in the TP (Tao et al. 2015), in southwest China (Li et al. 2012, Tao et al. 2017), in Sichuan Province (Zeng et al. 2016), and in arid regions of China (Yao et al. 2016).

There are several possible mechanisms for the relationship between the trends of regional precipitation and elevation in the HDMR. On the one hand, climate warming accelerates snow/glacier melting in higher elevation areas and increases local atmospheric water vapor, which consequently increases precipitation. For example, a mean temperature increase of 2°C is accompanied by precipitation increases up to 30% (Schär et al. 1996). In the HDMR, especially in the western Sichuan plateau, the snow cover, ice sheets, and permafrost thaws, local air humidity increases, and annual precipitation is changing at a higher rate than at lower altitudes (Yang et al. 2014, Tao et al. 2015). On the other hand, increases in anthropogenic aerosols are leading to a decrease in precipitation (Menon et al. 2002, Liu et al. 2011, Wang T et al. 2015, Wang H et al. 2015, Xie et al. 2016). Most of the aerosols are concentrated at relatively low elevations (below 3 km) (Ramanathan & Carmichael 2008). As a result, aerosols reduce low-elevation area precipitation, while the impact of aerosols on precipitation in high-elevation areas is small; thus the lower elevation areas have a greater drying trend. Socioeconomic development in the HDMR (especially as a result of the Chinese Western Great Development government policy after 2000) has led to increased aerosol emissions, thus exacerbating the drying trends in the lower elevation areas. However, it should be noted that although climate warming can lead to increases in precipitation, aerosols can result in a greater drying trend in low-elevation areas. Regional precipitation changes are regulated by modifications in large-scale circulation features such as storm tracks and monsoonal flows (Giorgi et al. 1997). These changes produce shifts in regional precipitation patterns, and therefore can lead either to increases or decreases in regional precipitation.

However, the sparsity of long-term observation stations (with >20 yr of observed records) has resulted

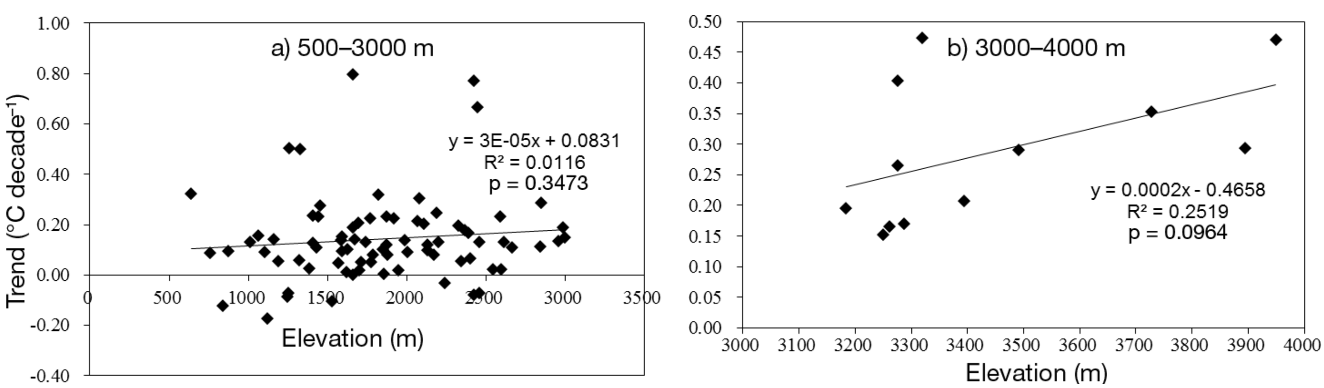


Fig. 12. Temperature trend magnitudes at elevations of (a) 500–3000 m and (b) 3000–4000 m in the Hengduan Mountain region. R^2: correlation coefficients for the relationships; p: statistical significance

in few studies being conducted in this region, especially in the high mountains (90 stations covering an area of 449 698 km^2 in the HDMR results in an average of only 5000 km^2 per station). Furthermore, there are no stations above 4000 m in the HDMR. The highest altitude for the HDMR is 7556 m. In order to record important changes in high-mountain areas by global observational networks, more stations should be set up in higher regions. Additionally, spatially continuous remotely sensed land surface temperature (LST) data from satellites (Lau et al. 2010), such as the Tropical Rainfall Measuring Mission (TRMM) data and model studies should also be used (Pepin et al. 2015). Moreover, due to the complexity of the mechanisms of elevation-dependency on temperature and precipitation, the trends should be further investigated using a combination of observational analyses and model research.

5. CONCLUSIONS

In this study, daily temperature and precipitation data from 90 meteorological stations in the HDMR were analyzed for the period of 1961–2011. We detected changes in annual, seasonal, and monthly temperature and precipitation, and conducted a detailed analysis of the relationships between the trends of temperature and precipitation and elevation in the HDMR. The main results can be summarized as follows.

T_{ann} increased by 0.16°C decade^{-1} during 1961–2011, exhibiting a significant warming trend. At the seasonal scale, warming trends were more apparent in winter, followed by autumn and summer, while spring showed the weakest trends. The temperatures increased by 0.27, 0.17, 0.14, and 0.09°C decade^{-1} in winter, autumn, summer, and spring, respectively. All 12 monthly mean temperatures increased, with trends ranging from 0.01–0.24°C per 10 yr. With regards to spatial distribution, the warming magnitudes were higher in the middle and north regions than the south during 1961–2011.

P_{ann} exhibited a nonsignificant decreasing trend of −11.41 mm decade^{-1} in the HDMR during 1961–2011. At the seasonal scale, precipitation decreased by −7.87, −8.90, and −2.07 mm per 10 yr in summer, autumn, and winter, respectively, and increased by 7.34 mm per 10 yr in spring. The HDMR showed a wetting trend during January–May, while a drying trend was observed during June–December.

The temperature increased by 0.06°C decade^{-1} per 1000 m for elevations ranging from 500–4000 m, showing an increasing trend with elevation during 1961–2011. The elevation dependency of climatic warming was most robust in winter, followed by spring, summer, and autumn, and the rates of increase in winter, spring, summer, and autumn were 0.10, 0.08, 0.07, and 0.03°C per 10 yr per 1000 m. The trend magnitudes of the monthly temperatures ranged from 0.02–0.10°C per 10 yr per 1000 m. The relationships between annual, seasonal, and monthly temperature trends and elevation indicated that there was evidence of elevation-dependent warming.

The annual and seasonal precipitation trends showed positive correlations with elevation. Precipitation increased by 7.8 mm decade^{-1} per 1000 m for altitudes ranging from 500–4000 m, showing an increasing trend with an increase in elevation during 1961–2011. The elevation dependences of the precipitation were 3.1, 2.0, 1.7, and 1.0 mm per 10 yr per 1000 m in summer, winter, spring, and autumn; only the values for winter precipitation were significant, indicating that the influence of elevation on seasonal precipitation was not marked except during winter. Although the annual and seasonal precipitation trends showed positive correlations with elevation, both annual and seasonal precipitation decreased except for spring precipitation, which increased significantly. The relationships between annual and seasonal precipitation trends and elevation indicated that higher altitude regions experienced a slower drying trend, and that the spring precipitation increasing trend was amplified with elevation.

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