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Variations of NDVI Over Elevational Zones During the Past Two Decades and Climatic Controls in the Qilian Mountains, Northwestern China

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Abstract

Trends of Normalized Difference Vegetation Index (NDVI) from 1982 to 2006 in the upper mountainous areas of three inland river basins (Shiyanghe, Heihe, and Shulehe, from east to west) in the Qilian Mountains, northwestern China, were analyzed based on the Global Inventory Monitoring and Modeling Studies (GIMMS) NDVI data. The relationships between NDVI and climatic factors such as air temperature, precipitation, and evaporation were also analyzed. The results indicate that changes of NDVI over time had an obvious elevational difference. NDVI has decreased in the northern lower-elevation (<3000 m) areas, which account for 31% of the total area, and increased in the southern higher-elevation (3000–4100 m) areas, which occupy 32% of the total area. In addition, 37% of the area did not show an obvious change in NDVI and was distributed in the periglacial belts with elevations higher than 4100 m. The decrease of NDVI in the lower elevations was controlled by a decrease in precipitation and an increase in air temperatures, whereas the increase in the higher elevations was mainly controlled by an increase in air temperature alone. With a continuous increase in air temperature in the future, vegetation would suffer from more serious water stress in the elevations lower than 3000 m, but become more flourishing between 3000 and 4100 m in the Qilian Mountains. This information is critical for understanding how climate warming may affect hydrology and ecology in the Qilian Mountains and for managing water resources for the lowlands in the Hexi Corridor adjacent to the mountains.

Introduction

Responses of vegetation to climate change have become increasingly important (e.g., Bonan, 2002; Eagleson, 2002; Cannone et al., 2007). Ecosystems are fragile and very sensitive to changes in temperature and precipitation particularly in high-elevation cold regions and parts of arid areas in the mid- and high latitudes (Diaz et al., 2003; Gottfried et al., 1998; Theurillat and Guisan, 2001; Cannone et al., 2007). In recent years, studies have indicated that both air temperature and precipitation directly determine the spatial and temporal variation and distribution of vegetation (Suzuki et al., 2000, 2006; Wang et al., 2001, 2003) and the Normalized Difference Vegetation Index (NDVI) (Gong and Shi, 2003; Piao et al., 2004; Yang et al., 2001; Suzuki et al., 2006; Fu et al., 2007; Song and Ma, 2008). In the high-elevation and cold regions, the returning-green date of vegetation has become earlier in spring in the last 20 years, and the NDVI appeared to increase (Myneni et al., 1997; Zhou et al., 2001; Bogaert et al., 2002; Lucht et al., 2002; Nemani et al., 2003; Jia et al., 2003; Tateishi and Ebata, 2004). In Alaska, the climatic warming has moved the treeline northwards and increased the density of trees (Hinzman et al., 2005). In the Alps, the climatic warming has moved forests upwards and made some species migrate from lower elevations to higher elevations (Keller et al., 2000; Theurillat and Guisan, 2001; Walther et al., 2005; Cannone et al., 2007; Lenoir et al., 2008). The NDVI has increased obviously in the northern and western parts of Qinghai-Tibet Plateau, but decreased in the southern and mid-eastern parts (Zhou et al., 2007). In the arid and semi-arid areas of Sahara, Mongolia, and Siberia, the climatic warming has improved the growth of vegetation in spring and autumn and extended the growth period. Meanwhile, it intensified the soil desiccation and restrained vegetation growth in summer (Suzuki et al., 2000; Yu et al., 2003; Anyamba and Tucker, 2005). In the Loess Plateau of China, the change in NDVI has experienced four stages (gradual increase, relative stability, rapid decrease, and rapid increase over the past 26 years), affected by both the climatic change and human activities (Xin et al., 2007).

Among these studies, there was a lack of studies on NDVI changes at different elevations and the response of NDVI change to the climatic change in mountains surrounded by arid regions. Such studies are particularly important for the inland river systems in the arid regions of northwestern China because they may provide useful information on understanding how vegetation changes in the mountains affect water cycling, particularly river flows to the lower reaches, and how climatic change affects migration of oases located in the mountain-front and the Gobi desert. The inland river basins of the northwestern China are unique when compared to any other river systems in the world mainly because the dynamics of oases in the Gobi deserts are

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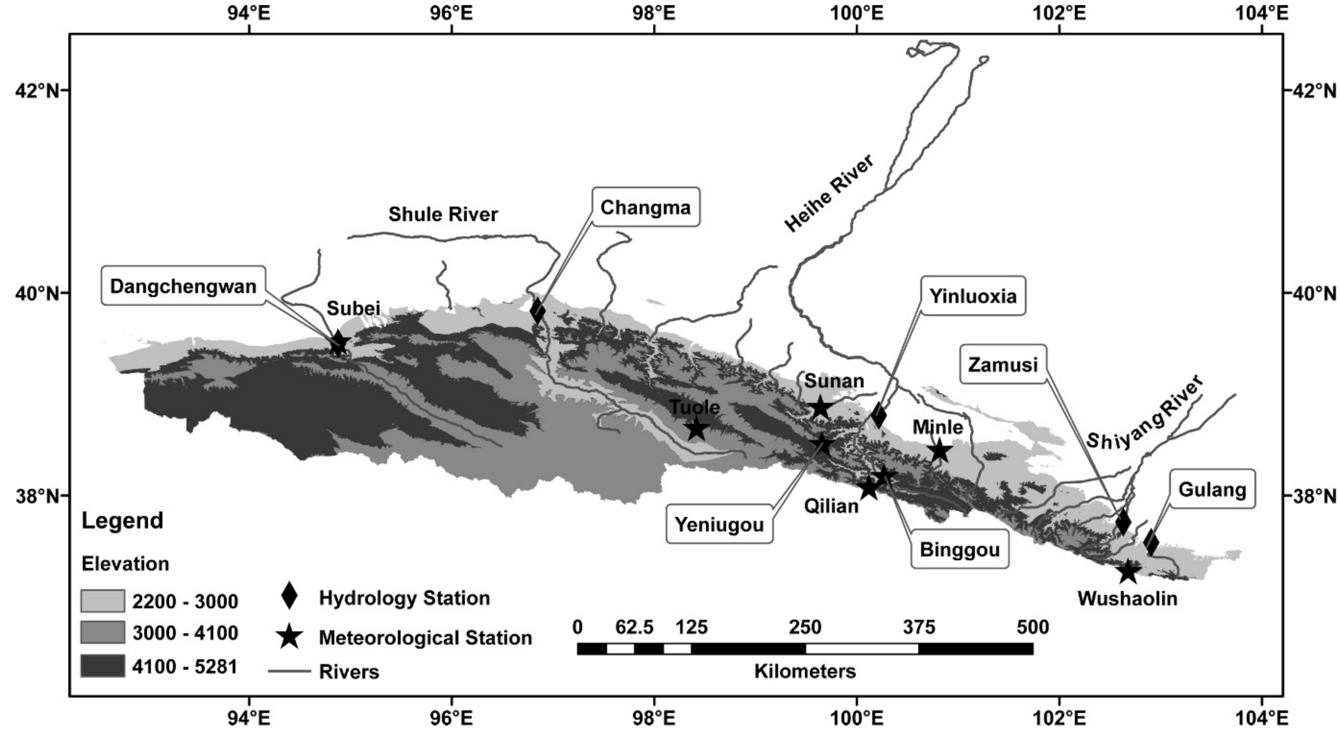

FIGURE 1. The study area, with meteorological and hydrological stations and major river systems.

controlled by water quantities they receive from rivers. Also, the inland river basins of northwestern China are characterized by cold and relatively wet climate for the mountainous areas and by relatively hot and extremely dry climate for oases at lower elevations. The mountainous areas of three inland river basins of the Hexi Corridor in western Gansu Province (east to Xinjiang) were selected for this study, namely Shiyanghe River, Heihe River, and Shule River basins. These basins are representative of inland river basins in the arid regions of the northwest China, including those in Xinjiang of westernmost China. Four questions were examined: (1) How did annual mean NDVI values change in the past 25 years? (2) How did annual mean NDVI values change with elevation? (3) How did monthly mean NDVI values change with elevation during the growing season? and (4) How are those changes related to climatic factors?

Study Area

The study area includes the mountainous part (above gauging stations in the mountain-front) of three inland river basins originating on the northern slopes of the Qilian Mountains, namely the Shiyanghe River, Heihe River, and Shule River, from east to west (Fig. 1). The Qilian Mountains are located at the northeastern edge of the Qinghai-Tibetan Plateau, with mean elevations of 4000–5000 m (Lan et al., 2001). The Qilian Mountains are "water towers" for the Hexi Corridor and a climatic divide for northwestern China. The elevations decrease sharply northwards to the Hexi Corridor with a great drop of 2000–3000 m in 30 km of horizontal distance. South of the mountains is a large basin, the Chaidam Basin. The Qilian Mountains are characterized by dry climate, with annual mean precipitation of 298 mm (since 1972) at Tuole meteorological station at an elevation of 3300 m. Precipitation and air temperatures vary significantly with topography. The annual mean air temperature was usually below 0 °C but higher in the south and north edges and lower in the central areas. Precipitation was greater in the southeastern part and lower in the western part (Yin et al., 2009). Permafrost was developed above 3400 m. The distribution of permafrost shows an obvious elevational zoning. The lowest elevation of continuous permafrost is 3600 m (Wu et al., 2007). Above 4100 m, glaciers were developed.

The mountainous portion of the three river basins ranges in elevation from 2200 to 5821 m, with a mean elevation of 3546 m and a combined drainage area of about 134,600 km^2. Elevations decrease in general from west to east and from south to north, with a periglacial belt above 4100 m mainly distributed in the western and middle parts and low mountains (<3000 m) distributed in the northern part. This portion is characterized by cold and long winters and short summers and autumns. The mean annual air temperature has been <4 °C and the mean annual precipitation has been 100–600 mm since 1972, with precipitation greater in the east than in the west. The distribution of vegetation shows an obvious vertical zoning. From 2000 m upward, the vegetation zones are divided as desert steppe zone (2000–2300 m), steppe zone (2300–2600 m), forest steppe zone (2600–3200 m), bushvela steppe zone (3200–3700 m), meadow steppe zone (3700–4100 m), and snow belt (>4100 m) (Zhang and Guo, 2002).

Data and Sources

NDVI DATA

The NDVI data were generated globally by the Global Inventory Monitoring and Modeling Studies (GIMMS) group, with an 8-km spatial resolution and 15-day temporal resolution (Pinzon, 2002; Tucker et al., 2005). The data set spans from January 1982 to December 2006. The data set was produced using a maximum merged method, which reduced the cloud impact during the El Chichon and Mt. Pinatubo volcanic stratospheric aerosol periods. A stratospheric aerosol correction was applied as proposed by Vermote et al. (1997) from April 1982 through December 1984 and from June 1991 through December 1994

(Pinzon, 2002; Pinzon et al., 2004; Tucker et al., 2005). The projection uses Albers Equal-Area Conic Projection. The NDVI data set was produced using the maximum value compositing (MVC) procedure (Holben, 1986), which eliminates the effects of clouds on the data (Hope et al., 2003; Stow et al., 2004). The NDVI data in the growing seasons from April to October were chosen and processed because the vegetation coverages were low in the non-growing seasons in the mountainous areas, and the NDVI values were subject to the influence of snow and soil reflectance (Chen et al., 2008).

METEOROLOGICAL DATA

Air temperature, precipitation, and 20-cm pan evaporation from 1982 to 2006 were collected from seven national meteorological stations, three of which are located in lower elevations (2100–2400 m) and the other four in the mid- and high elevations (2800–3400 m) (Fig. 1). Additional measurements of air temperature and precipitation were conducted from 1985 to 1993 at an observatory site at Binggou Basin in the Heihe Runoff Experimental Area (Zhang and Yang, 1991; Yang et al., 1993). The data at the Binggou Basin were only used to analyze changes of air temperature, precipitation, and wetness with elevations, but not for the relationship between NDVI and air temperature and precipitation due to their limited temporal coverage.

DEM

SRTM-3 DEM with a 90-m spatial resolution was used in this study. The original geographic coordinate system was transformed into Albers Equal-Area Conic Projection to match the GIMMS NDVI data. The boundaries of the upstream mountainous area were extracted using the D8 algorithm (Tribe, 1992), using hydrometric stations in the mountain-front as pour points.

Methods

TREND OF NDVI

A univariate linear regression method was used to analyze the temporal trend of NDVI, which uses time and NDVI as independent and dependent variables, respectively. The slope of the linear regression was used to illustrate the trend of NDVI (Stow et al., 2003). The slope was calculated as:

$$\mathrm{SLOPE} = \frac{25 \times \sum_{i=1}^{25} i \times \mathrm{NDVI_i} - \left(\sum_{i=1}^{25} i\right)\left(\sum_{i=1}^{25} \mathrm{NDVI_i}\right)}{25 \times \sum_{i=1}^{25} i^2 - \left(\sum_{i=1}^{25} i\right)^2} \quad (1)$$

where NDVI is either a mean annual or mean monthly value. For inter-annual variation, $\mathrm{NDVI_i}$ is the mean annual (April–October) value of each grid from 1982 to 2006, and *i* represents year. For the monthly trend, NDVI is the monthly mean value of each grid for the April–October period each year, and *i* represents year as well.

Based on Ma et al. (2003), the trend was considered to decrease over time if SLOPE ≤ -0.05 and increase if SLOPE > 0.05; otherwise, the trend was considered as non-changing over time.

CORRELATION BETWEEN CLIMATIC FACTORS AND NDVI

Using meteorological data from seven weather stations, the response of NDVI to climatic change was analyzed using correlation analysis. To extract the NDVI values at these sites, a smoothing algorithm with 3 × 3 grids was performed to eliminate the local effects of human activities on the vegetation change. The mean NDVI values centered on the seven weather stations were calculated, and the correlation between NDVI and air temperature and precipitation was performed.

Results

VARIATION OF CLIMATIC VARIABLES

Variation of Annual Precipitation, Temperature, and Evaporation

The meteorological data showed that there was no significant trend for annual precipitation over the past 25 years at all seven stations (Figs. 2a and 2b). However, air temperature has significantly increased over the past 25 years ($R^2 = 0.48$–0.72, $p < 0.01$), with a mean rising rate of about 0.71 °C/10 a and 0.63 °C/10 a for the lower- and higher-elevation stations, respectively (Figs. 2c and 2d). The mean annual evaporation slightly increased over the past 25 years at all stations (Figs. 2e and 2f), but the increase was significant only at Minle, Wushaoling, and Tuole stations ($R^2 = 0.24$–0.30, $p \leq 0.01$).

Variation of Monthly Precipitation, Temperature, and Evaporation

Monthly mean air temperature from April to October has all increased since the early 1980s in lower and higher elevations (Figs. 3a and 3b). The rising temperature was significant from June to August at lower elevations ($R^2 = 0.33$–0.55, $p < 0.01$), with a rate ranging from 0.68 to 1.02 °C/10 a. The rising temperature was significant from April to September except for May at higher elevations ($R^2 = 0.26$–0.51, $p < 0.01$), with a rate ranging from 0.71 to 0.97 °C/10 a. The rising temperature has also resulted in an increase in evaporation. However, the increase of the mean evaporation of three meteorological stations at lower elevations was significant only in June ($p < 0.01$), with a rate of 26.6 mm/10 a (Fig. 3c).

Variation of Precipitation, Temperature, and Pan Evaporation with Elevation

Annual mean precipitation, temperature, evaporation, and wetness index (ratio of precipitation and potential evaporation following Suzuki et al. [2006], with a modification that actual evaporation was used instead due to the lack of complete potential evaporation data set) were well correlated with elevations over the past 25 years (Fig. 4). With an increase in elevation from 2159 to 3450 m, annual mean air temperature decreased from 7.2 to −2.3 °C (Fig. 4a), while annual total precipitation increased from 151.2 mm to 509.3 mm (Fig. 4b) and annual mean pan evaporation decreased from 2581 mm to 1116 mm (Fig. 4c). Annual mean wetness index increased from 0.06 to 0.46 (Fig. 4d).

VARIATION OF NDVI VALUES

Spatial Distribution of NDVI

Distribution of annual mean NDVI values from 1982 to 2006 showed an obvious spatial difference from east to west (Fig. 5). To the east of 98°E, NDVI values ranged from 0.2 to 0.5, while to the west of it, all NDVI values were less than 0.2. Therefore, vegetation coverage in the eastern part of the study area was better than that in the western part. In other words, vegetation coverage was better in the upper Heihe River and Shiyanghe River

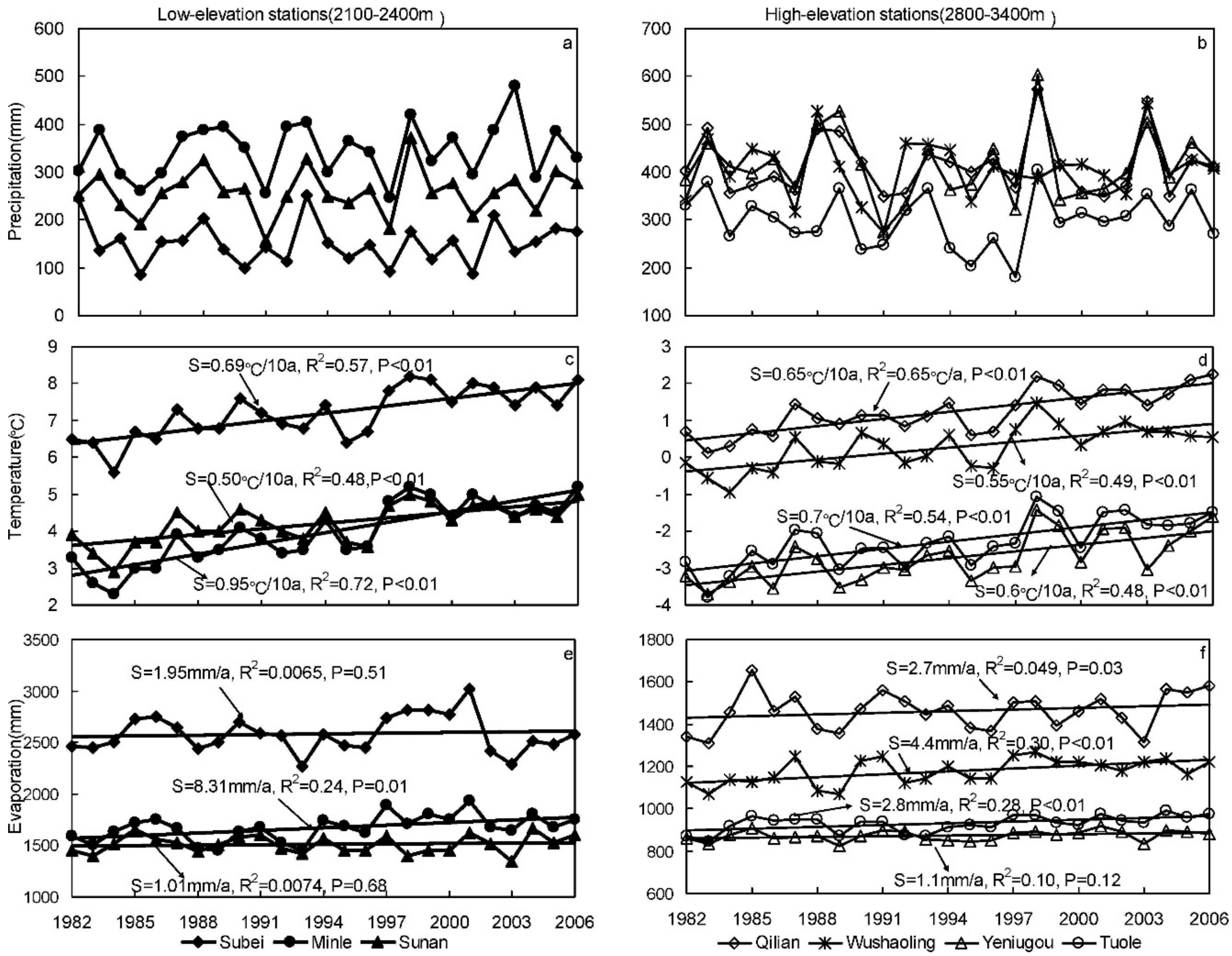

FIGURE 2. Variation of annual mean precipitation, temperature, and evaporation from 1982 to 2006 (S represents slope).

Basins, compared to that in the Shulehe River Basin. This result was consistent with the spatial pattern of precipitation, i.e. drier in the west and wetter in the east of the Qilian Mountains.

Temporal Variation of Annual NDVI Values

Annual mean NDVI values showed a different temporal trend from south to north with variation of elevations. In the northern lower-elevation areas below 3000 m, the trend of the annual mean NDVI values was dominated by a decline over the past 25 years (Fig. 6), with a decrease in 60–90% of the area and an increase in only 10–35% of the area (Fig. 7). The average decline of NDVI occurred at a rate of 0.008/10 a (R^2 = 0.41, p < 0.01) (Fig. 8). From 3000 to 4000 m, the trend of the annual NDVI values turned to increase in 40–60% of the area and to decrease in less than 30% of the area (Figs. 6 and 7). The annual mean NDVI values increased 0.012 every 10 years (R^2 = 0.67, p < 0.01) (Fig. 8). Higher than 4100 m in the periglacial belt, the annual mean NDVI values did not significantly change (Fig. 6), with a decrease in <20% of the area and an increase in <10% of the area (Fig. 7).

Monthly Variation of NDVI Values in the Growing Season

Trend of monthly mean NDVI values over the past 25 years was calculated for April to October (Fig. 9). The slope values of the linear trend showed that the monthly mean NDVI values increased mainly from April to June and varied spatially from north to south from July to September, and were almost unchanged in October. In April, 51% of the area tended to increase in NDVI, 26% did not change, and 23% tended to decrease. In May, the percentages of area with increased, unchanged, and decreased NDVI values were 57, 26, and 17%, respectively. In June, the above percentages were 63, 14, and 22%, respectively. From July to September, NDVI values mainly showed a decrease in the northern, lower-elevation areas, and an increase in the southern mid- and higher-elevation areas. In general, decrease was the dominant trend of NDVI values during July–September with the percentages of 52, 48, and 96%, respectively. In October, 61% of the area did not show any changes in NDVI values.

Discussions

CONTROLS OF TEMPORAL VARIATION OF ANNUAL MEAN NDVI VALUES ALONG ELEVATION ZONES

The temporal variation of NDVI values over the past 25 years showed a spatial pattern with elevations, with a decrease of NDVI values mainly in the lower elevations (<3000 m) and an increase mainly in the mid and higher elevations (3000–4100 m). In the lower elevations, there was a significant positive correlation between precipitation and NDVI values (Fig. 10a). At the Subei station, where the annual mean precipitation was the lowest (151.72 mm), the correlation was the greatest, with R^2 = 0.49 (n =

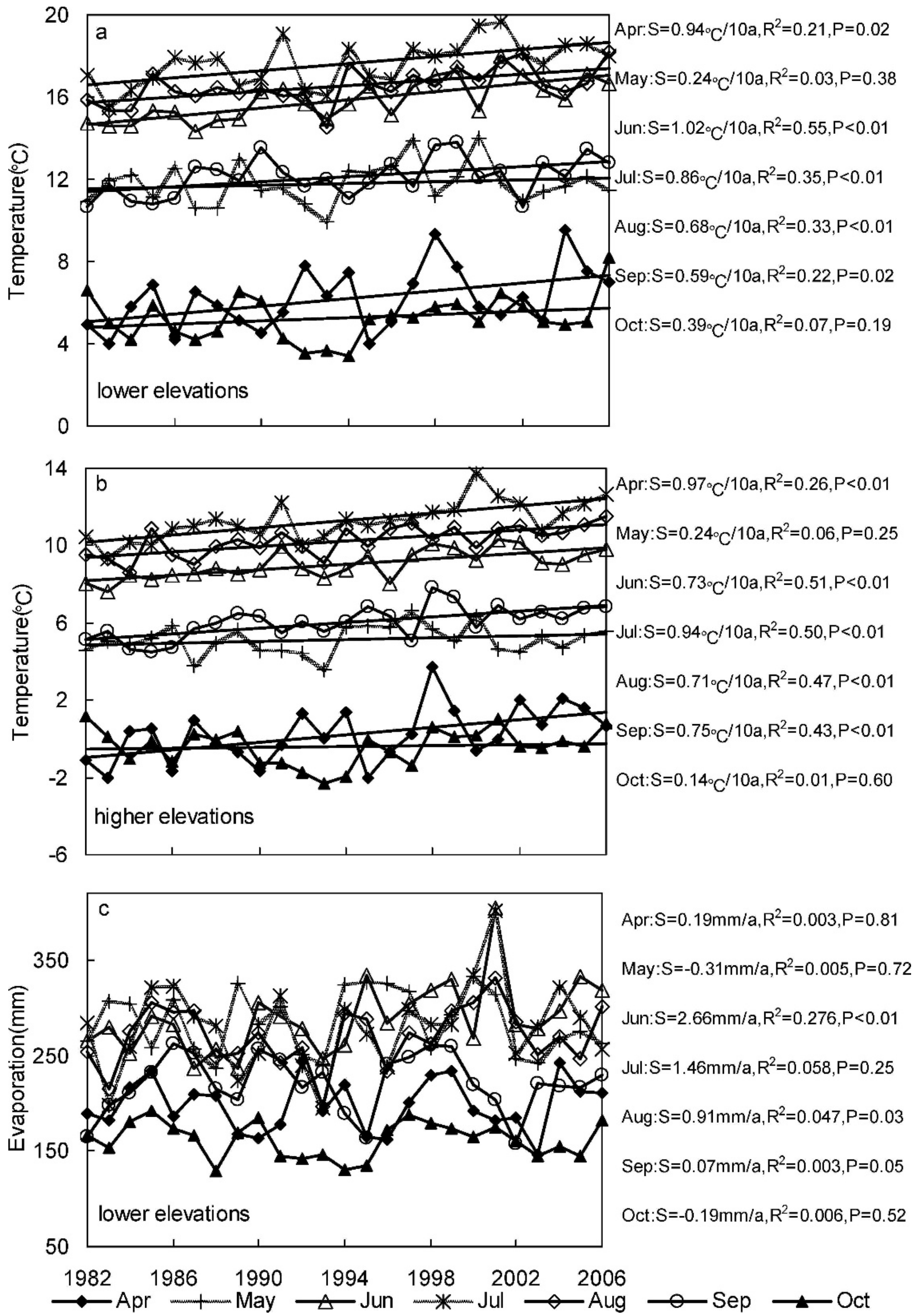

FIGURE 3. Changes of monthly mean air temperature from April to October in (a) lower and (b) higher elevations and (c) changes of monthly mean evaporation, averaged from three stations at lower elevations (S represents slope).

25, $p < 0.01$). The R^2 values were 0.46 and 0.28 ($n = 25$, $p < 0.01$) at the Sunan and the Minle stations, respectively. The correlations between air temperatures and NDVI values at lower elevations were negative and significant at Subei and Minle stations ($n = 25$, $R^2 = 0.24$ and 0.25, $p = 0.01$) (Fig. 10b). The increase in air temperature resulted in an increase in evaporation (Figs. 2e and 2f) and thus a decrease in NDVI at lower elevations, consistent with Xin et al. (2007) and Jolly et al. (2005). Therefore, the change of NDVI values was controlled by changes in both precipitation and air temperature in the lower elevations.

This result is consistent with that of Siberia. In a 75°E transect from 40° to 60°N in Siberia, NDVI values had a

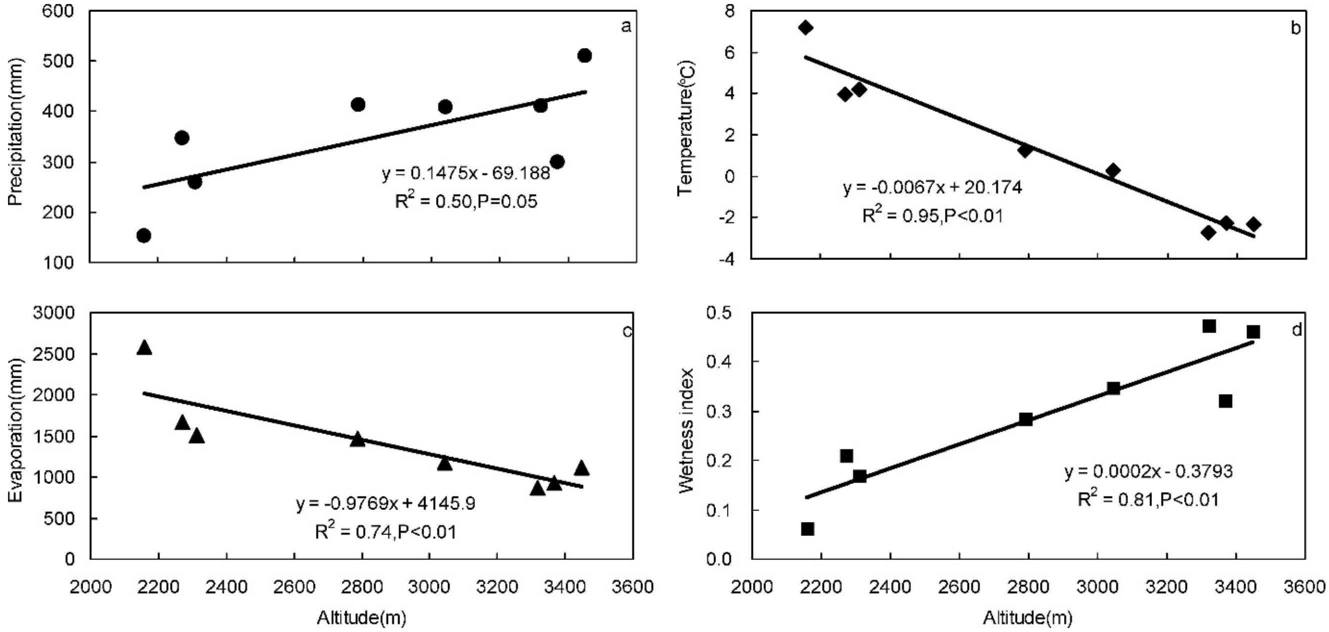

FIGURE 4. Change of annual mean climatic factors from 1982 to 2006 with change in elevations at the weather stations.

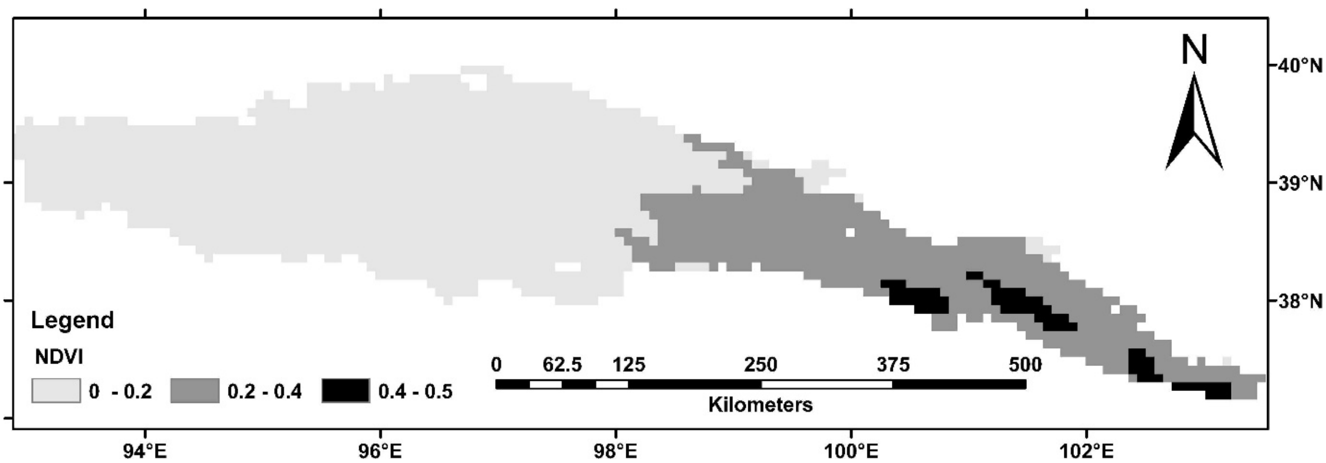

FIGURE 5. Distribution of mean NDVI values averaged from 1982 to 2006.

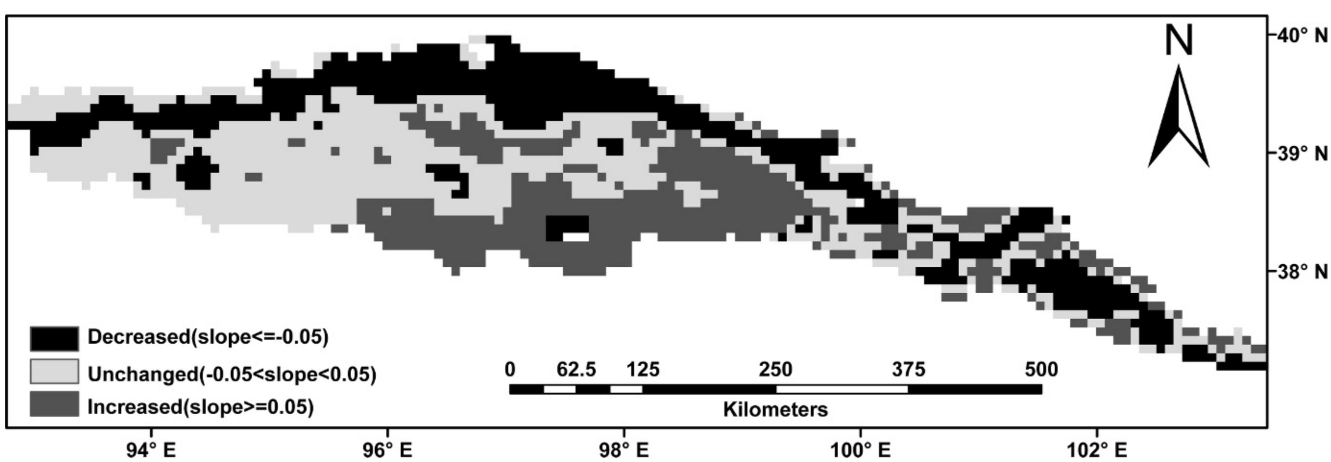

FIGURE 6. The trend of NDVI values in the mountainous areas from 1982 to 2006.

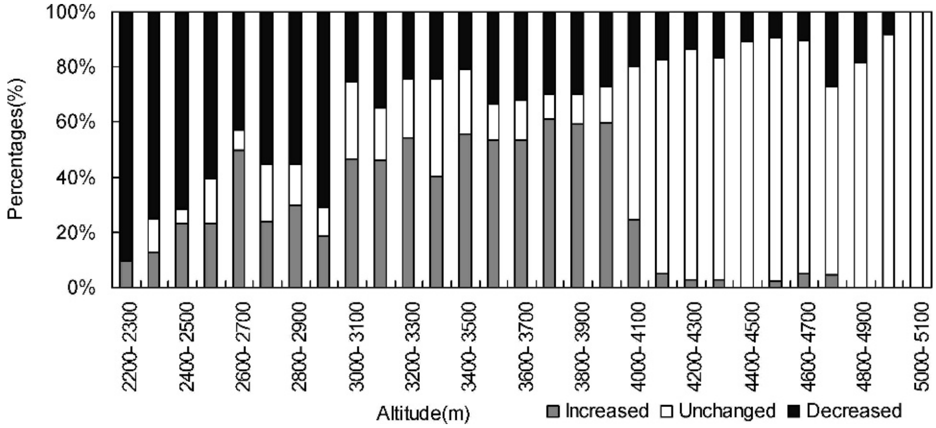

FIGURE 7. The percentages of area for NDVI changes in different elevation zones.

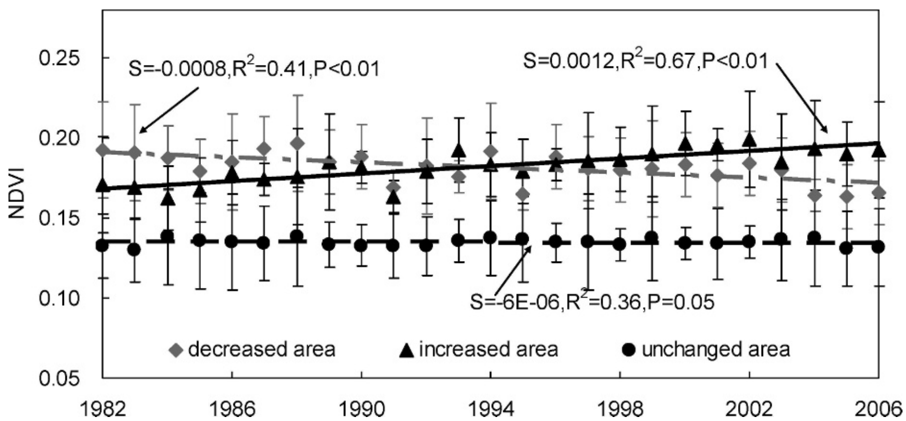

FIGURE 8. Trends of annual mean NDVI for the increased, decreased and unchanged areas.

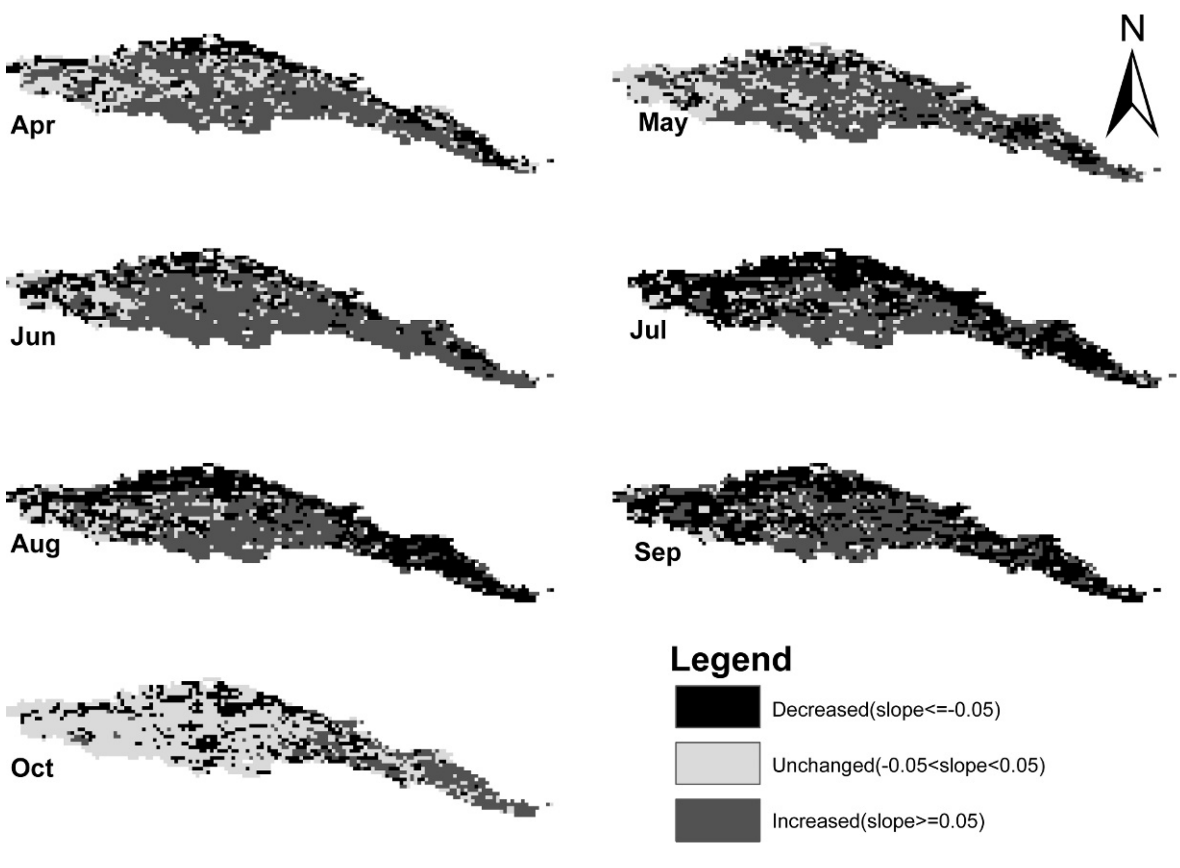

FIGURE 9. Monthly variation of NDVI values in growing seasons from 1982 to 2006.

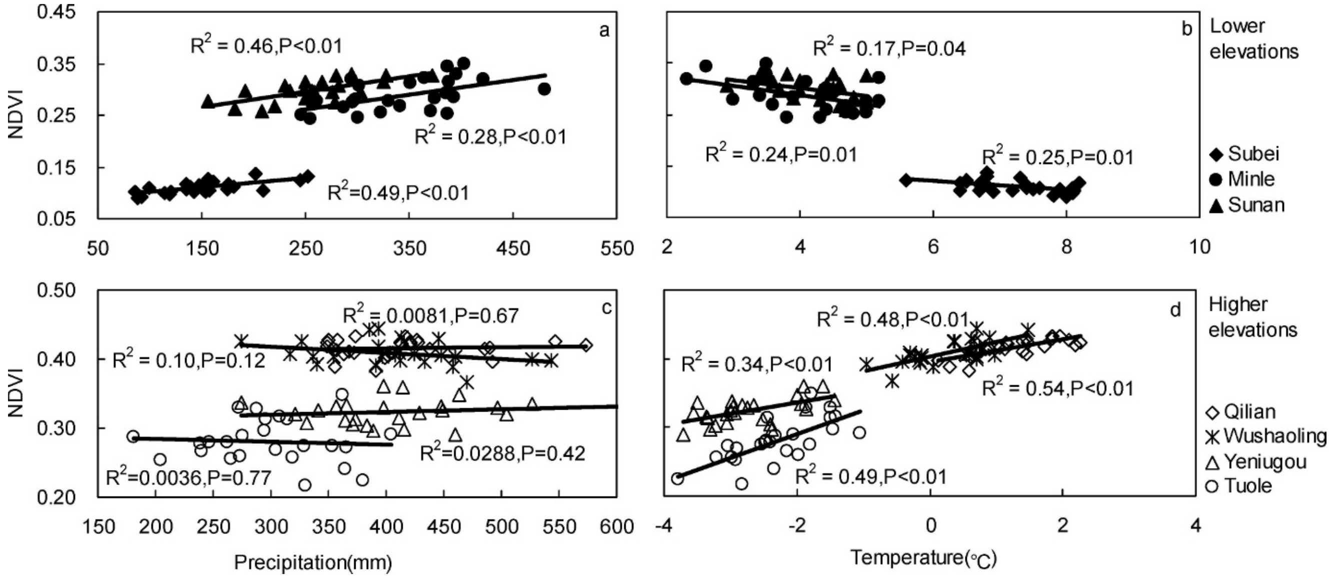

FIGURE 10. Correlations of NDVI values and climatic factors in the lower-elevation, moderate, and higher-elevation areas.

significant positive correlation with precipitation ($R^2 = 0.79$, $p < 0.05$) and a significant negative correlation with air temperature ($R^2 = 0.58$, $p < 0.05$) (Suzuki et al., 2000). However, this result is somewhat different from the other arid regions such as Sahara and Mongolia. Impacted by increase of air temperature, the time of greening onset of vegetation has become earlier in Sahara and precipitation has become the main factor influencing the change of NDVI values in the late period of vegetation growth (Anyamba and Tucker, 2005). Similarly, precipitation was also the major factor affecting the change of NDVI values in the Mongolia Prairie (Yu et al., 2003).

In higher elevations (2800–3400 m), there was no significant correlation between NDVI and precipitation (Fig. 10c), but there was significant positive correlation between NDVI and air temperatures, with $R^2 \geq 0.34$ and $p < 0.01$ for all stations (Fig. 10d). Therefore, the change of NDVI values was mainly impacted by air temperature at higher elevations and precipitation is not a limiting factor. The increase of air temperature led to earlier snowmelt and an increase in snow-free days, resulting in earlier greening onset of vegetation and strengthening of vegetation growth in summer and autumn. Thus, the NDVI showed an increasing trend from 3000 to 4000 m, which is also supported by Zhang et al. (2007) and Jolly et al. (2005). Research on vegetation change in the Arctic showed that the distribution of vegetation was controlled by air temperature. With an increase of air temperature, NDVI also increased (Raynolds et al., 2008). In the Siberian tundra, there was a significant correlation between NDVI and air temperature (Suzuki et al., 2006). In the Alps, the growth rate of shrubs increased at 5.6%/10 a at the elevation of 2400–2500 m with an increase of air temperature (Cannone et al., 2007). The inter-annual change of vegetation had a close relationship with air temperature in the source region of the Yangtze River and the Yellow River, as well as the eastern section of the Qinghai-Tibet Plateau (Yang et al., 2006; Zhou et al., 2007).

CONTROLS OF MONTHLY NDVI TEMPORAL TRENDS

The temporal trend of NDVI values also shows a seasonal difference from April to October, again controlled by both precipitation and air temperature. From April to June, increase of NDVI was the dominant trend for the study area as a whole. Air temperature increased at low (Fig. 3a) and high elevations (Fig. 3b), with an increase rate of 0.96 °C/10 a, 0.24 °C/10 a, and 0.88 °C/10 a in April, May, and June, respectively. The increase of air temperature in spring led to more snowmelt and better vegetation growth (Myneni et al., 1997; Zhou et al., 2001; Tateishi and Ebata, 2004). The rising rates of air temperature were 0.86 °C/10 a, 0.68 °C/10 a, and 0.59 °C/10 a at lower elevations in July, August, and September, respectively (Fig. 3a) and 0.94 °C/10 a, 0.71 °C/10 a, and 0.75 °C/10 a at higher elevations in July, August, and September, respectively (Fig. 3b), resulting in an increase in evaporation. Evaporation increased at 1.46 mm/a, 0.91 mm/a, and 0.07 mm/a at lower elevations in July, August, and September, respectively (Fig. 3c). Due to an insufficient amount of precipitation and the increase of air temperature and evaporation at the lower elevations, water needed for growth of vegetation was limited and NDVI decreased. In the southern mid- and higher-elevation areas, precipitation was comparatively plentiful. The increase of air temperature favored photosynthesis and the growth of vegetation (Yang et al., 2006; Zhou et al., 2007; Raynolds et al., 2008). Thus, NDVI increased in higher elevations from July to September. In October, the increase of air temperature was at 0.39 °C/10 a for the low-elevation stations (Fig. 3a) and 0.14 °C/10 a for high-elevation stations (Fig. 3b). But the change of NDVI was not obvious, which means that the slight increase in air temperature in October did not change much of plant physiology and extend the growing season.

Conclusion

With an increase in air temperature in the past two decades or so in the Qilian Mountains, vegetation intensity has become somewhat decreased due to water stress in the lower elevations, but has flourished in the higher elevations as a result of enhanced photosynthesis. This trend would continue and the greening zone may move upwards with a continuous increase in air temperature. Flows of mountain streams may be reduced due to an increase in evaporation and water use by plants at the higher elevations. Since the Qilian Mountains are water towers for the lowlands in the Hexi Corrdor and the Gobi Deserts, the water stress that those regions have been suffering may be worsened in the future.

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