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Precipitation trend–Elevation relationship in arid regions of the China

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ABSTRACT

Based on monthly precipitation data at 128 meteorological stations in the arid regions of the China (ARC), we investigated that the regional characteristics of precipitation trend and the precipitation trend–elevation relationship during the period of 1961–2012. There is growing evidence that the elevation-dependent wetting (EDWE), which is the precipitation wetting trend is amplified with elevation. The precipitation trend increases significantly with elevation except for the altitude from 500 to 1500 m, the highest correlation appears above 1500 m, increases by 13 mm/decade with each 1000 m. With the elevation increasing every 1000 m, precipitation tendency rate increases by 7 mm/decade from 1000 to 2000 m and increases by 10 mm/decade from 2000 to 4000 m. EDWE has an impact on the change of the cryospheric systems, ecosystems and water resources, especially in arid regions of China. We discuss mechanisms that contribute towards EDWE: water vapor changes and warming-driven water circulation speeds up. We suggest future needs to increase evidence of understand the EDWE in other mountainous regions, and its controlling mechanisms through integrated the observational network of surface in-situ climate observations, satellite data and high-resolution climatic modeling.

1. Introduction

High mountains cover about one-fifth of continental regions (Beniston et al., 1997; Price and Butt, 2000), and they provide the habitat for many of the world's rare and endangered species (Mountain Research Initiative EDW Working Group, 2015), and as ‘water towers’ of many major river systems, especially important in arid regions (Beniston et al., 1997; Chen, 2014a,b; Yao et al., 2015a,b). Moreover, it promotes the vulnerability of ecosystem and cryospheric systems with increasing elevation (Ohmura, 2012). The Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC 2013) indicated that the climatic system is significantly changing and further impacting the environment, water resources, and human lives (Shi and Xu, 2008). A majority of evidence for climate change may be more accumulated with increasing elevation (Barry, 1992). Mountains precipitation is important components of the hydrologic cycle, as they have important contributions to the water balance of river systems originating in mountain regions, also to the populations living downstream and existing socio-economic structures (Beniston et al., 1997).

Climate changes in the main mountain regions have been reported over the past decade. A preponderance of studies suggested that climatic warming is more rapid at higher elevations. Mountain Research Initiative EDW Working Group (2015) reviewed a growing evidence that the warming rates was amplified with elevation, also known for short as elevation-dependent warming (EDW), such that the temperature in high-mountain regions occur more rapid changes than at lower elevations. Ohmura (2012) showed the enhanced temperature variability in high-altitude in 10 major mountain regions of the world, such as Alps, Tibet, Himalayas, Tianshan, Kashmir, Andes, Qilianshan, and the North American Cordillera and the Appalachians. Dong et al. (2014) indicated the temperature trends change with elevations in China. Yan and Liu (2014) investigated that the annual mean temperature has a systematic increases with elevation on and around the Tibetan Plateau. Li et al. (2012) examined the increased precipitation mainly at high-mountain regions in southwestern China. Concurrently, precipitation trends change with elevation becomes more complex owing to the influence of topography and atmospheric circulation. The arid region of China, herein referred to as ARC, is an important component of the Central Asia, and holds a strategical important position in China's Silk Roads Economic Belt (SREB), responds sensitively to global climate change (Ding et al., 2007; Chen et al., 2012, 2014, 2015). It extends between 34–50°N and 73–108°E, with an area of 2.5 million km^2, with a unique physiography featured by three large mountain ranges separated by two vast basins (Deng et al., 2014; Yao et al., 2015a,b). The complex topography and large mountain areas in ARC with huge latitude span are influenced by multiple circulation systems and especially sensitive to climate change. Generally, climate change in complex mountain regions will be expected to seriously affect water resources in arid regions (Deng et al., 2015). Therefore, the studies of precipitation

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change with elevation in ARC not only deepens the understanding of global warming, but also contributes to the study of hydrologic cycle, ecological environment, and climate change regionally and globally (Dong et al., 2014). Based on the newest results, Chen et al. (2015) reviewed the progress and prospects of climate change in ARC, and indicated that the temperature and precipitation experienced “sharply” increasing in the past 50 years. Li et al. (2013) found that the mountain precipitation had a fastest increasing rate. Deng et al. (2015) uncovered the relationship of climate change with elevation in the Tianshan Mountains. Therefore, the previous climate change study in ARC has concentrated on precipitation trends, and little attention has been paid to precipitation with elevation. This article employs observation to investigate the spatial characteristics of the precipitation trends as well as its seasonal characteristics, explores whether its relation with elevation is significant, and reveals preliminarily the causes. The objective of this paper is to investigate the regional characteristics of precipitation trend and the precipitation trend–elevation relationship in ARC during the period of 1961–2012 as a case study. We discussed the possible physical mechanisms and future needs to increase knowledge of mountain precipitation changes.

2. Data and method

Continuously observed dataset of 128 meteorological stations covering the arid region of northwest China (ARC) were provided by the National Climatic Center of the China Meteorological Administration (NCC-CMA). These stations are national basic stations of the CMA and are distributed across in Xinjiang autonomous province, Gansu province, Qinghai province and Inner Mongolia autonomous province of the China (Fig. 1). This study focuses on the daily precipitation data from 1961 to 2012. All the meteorological data collected for this work maintained the standard requires strict quality control processes and homogeneity assessment of the National Meteorological Administration of China (NMAC). The processes including the standard normal homogeneity test (Alexandersson, 1986), the moving *t*-test (Peterson et al., 1998), and the departure accumulating method (Buishand, 1982).

The distribution of 128 meteorological observation stations with respect to elevation in ARC is shown in Fig. 2, located from near sea level (Toksun station, 1 m) to 3539 m (Daxigou station), from 34.9°N to 49.3° N and 73.7°E to 106.8°E. Immerzeel et al. (2010) indicated that the regions above 2000 m are the main water supply areas in Asia. Yao et al. (2015a,b) showed that the regions above 1500 m as the threshold to define the mountain areas in ARC. For this region, 98 of the stations are below 1500 m, 30 are above 1500 m, and especially 14 are above 2000 m. Moreover, 14 are on the Tianshan Mountains, and 16 are on the Qilian Mountains.

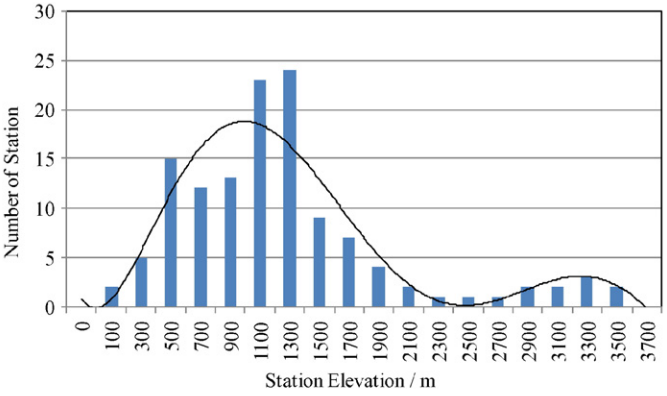

Fig. 2. Numbers of national meteorological stations at different altitude.

In this paper, the gradient plus inverse distance squared (GIDS) was selected as one of the interpolation methods to interpret the spatial distribution of the annual total precipitation (ATP). GIDS, which combines multiple linear regression and distance- weighting, was simple to apply and avoided the subjectivity involved in defining variogram models and neighbourhoods (Nalder and Wein, 1998; Yao et al., 2015a,b). Fig. 3 showed that the high value of the ATP is distributed from the mountainous area of the ARC, including the Tianshan Mountainous Area (TMA), Qilian Mountainous Area (QMA), and Altai Mountainous Area (AMA), especially in the Ili Valley and Northern AMA. The precipitation patterns are consistent with the pattern of elevation.

We used the Mann–Kendall nonparametric statistical test to detect the trends in the time series of precipitation in ARC (Mann, 1945; Kendall, 1975; Chen et al., 2014; Yao et al., 2015a,b).The Pearson's correlation test has been widely used in long-term series correlation

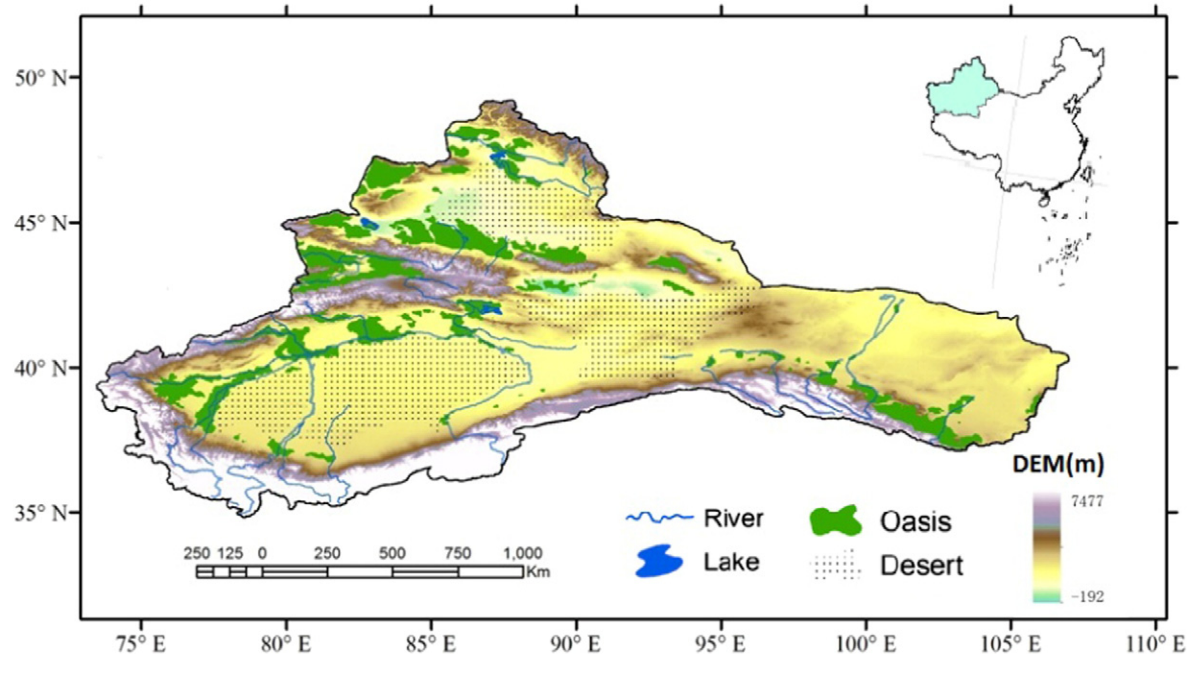

Fig. 1. Location of the arid region in China.

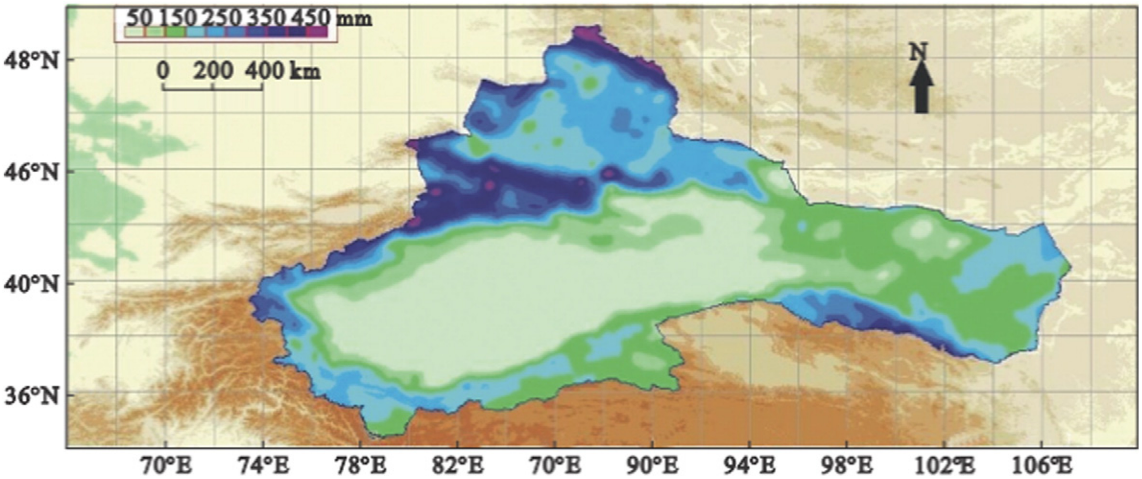

Fig. 3. Spatial distribution of ATP in Northwest China (Yao et al., 2013).

analysis (Li et al., 2013). In this study, we employed it to detect the correlation coefficient between the precipitation trend and elevations.

3. Results

3.1. Precipitation trend characteristics

Fig. 4 shows the spatial patterns of the trends and trend magnitudes of the ATP in ARC for the period of 1961–2012. The Mann–Kendall method indicated that the ATP has increased by 9.31 mm/ decade, showing a significant wetting trend at the 99% significance level. The statistical results indicated that the wetting station reaches the 93.8%, and 49.2% reach the 95% significance level (Table 1). Among the different seasonal, wetting occurs in all seasons, the magnitudes of increases most significantly in summer and spring than in the other two seasons. The number of wetting stations reaches maximum in winter, up to 97.6% stations experience wetting, and only accounting for 2.4% experience drying. In summer, although the precipitation increases most significantly, and the number of drying stations reaches maximum, accounting for 23.4% of the total stations.

Fig. 4 shows the spatial distributions of the temporal trends in ATP. The significant wetting was found in the whole region, while the higher magnitudes of wetting in the mountainous area, i.e., up to 52.5 mm/ decade in Yeniugou stations of the QMA and 28.3 mm/ decade in Xinyuan stations of the TMA. Considering the regional characteristics, QMA had the highest wetting rate of 38.7 mm/ decade, followed by the TMA and AMA, with a rate of 16.8 and 12.3 mm/decade, and Southern Xinjiang (SXJ) and Western Inner Mongolia (WIM) has the lowest rate of 5.44 and 5.09 mm/decade, respectively. The Mann–Kendall method revealed that the increasing trends are statistically significant at the 99% significance level, except for the WIM.

3.2. Precipitation trend–elevation relationship

According to the spatial distribution patterns of the ATP trend, we discuss the predominant factors: elevation, latitude or longitude. In general, climate sensitivity increases in high latitudes region due to the influence of changes in albedo and energy budgets (Zhai and Ren, 1997), and the longitude was also the main geographical causes of precipitation trends distribution due to the land–sea distribution and distant (Fang, 1992). The statistical relationships between precipitation trends

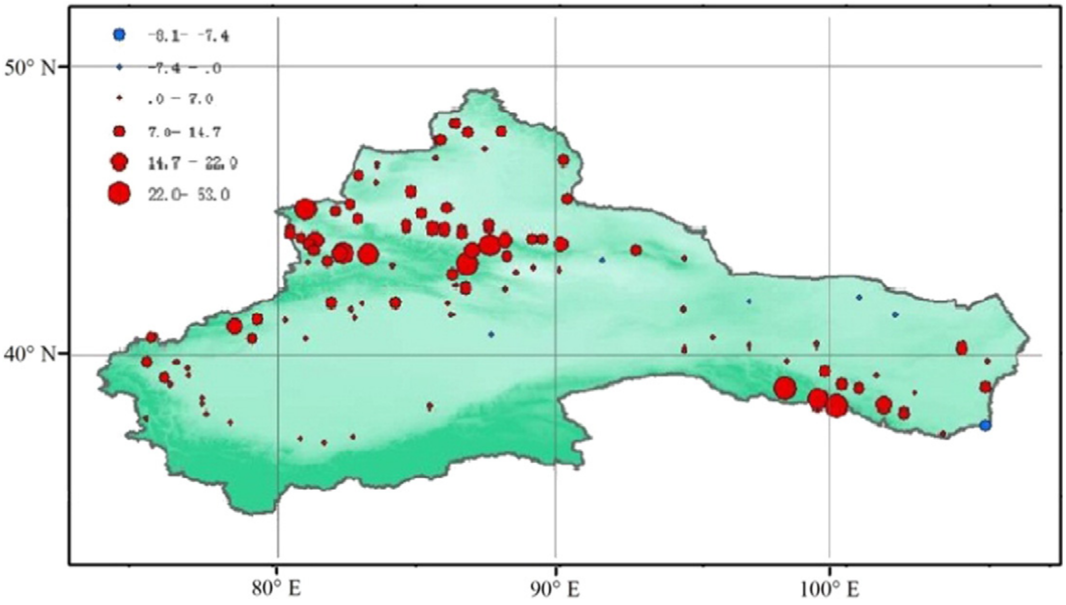

Fig. 4. Distribution of ATP trend in ARC (Yao et al., 2013).

Table 1
Numbers of stations and precipitation trends on an annual and seasonal basis.

Time period	Wetting			Drying		
	Number	Precipitation trend/(mm/10a)	Number< 95% significance level	Number	Precipitation trend/(mm/10a)	Number< 95% significance level
Annual	120	11.39	63	8	2.31	0
Spring	113	3.66	32	15	0.34	0
Summer	98	4.28	26	30	2.24	2
Autumn	106	2.91	37	22	0.84	1
Winter	125	2.33	88	3	0.01	0

and latitude, elevation and longitude were investigated in ARC over the period of 1961–2012. The results showed that the precipitation trends had closely tied with the elevation ($R = 0.49$, $p < 0.001$, Fig. 5a), but do not significantly vary with longitude and latitude ($R < 0.1$, $p > 0.1$). A possible reasons for that the unique “mountains-basins landscape”, is a strong spatial heterogeneity in the hydro-climatic conditions, determines the uneven spatial distributions of the precipitation trends. Further, the correlation between latitude (and longitude) and precipitation trends using the elevation below 1500 m was calculated and shown in Fig. 5(b and c). The results presented that the precipitation trends was linearly positively related to the latitude ($R = 0.51$, $p < 0.001$), while the negatively related to the longitude ($R = -0.36$, $p < 0.01$). Thus, these results further demonstrated that the predominant factors of controlling water variability distribution in ARC are elevation, which is consistent with previous studies (Chen et al., 2015; Yao et al., 2015a,b; Deng et al., 2015). Therefore, in the following, only needs to be studied the relationship between precipitation trend and elevation.

The relationships between precipitation trend and elevation are studied at different altitudinal zones with different intervals. These stations are divided into three different intervals with elevation: 500 m, 1000 m and 1500 m intervals. According to this, precipitation trends from low to high elevation ranges are shown in Figs. 6–8. The precipitation trend increases significantly with elevation except for the elevation from 500 to 1500 m, the highest correlation appears in the mountain areas (above 1500 m), precipitation tendency rate increases by 13 mm/decade with each 1000 m increase of altitude, and the correlation coefficient is 0.68 ($p < 0.001$) (Fig. 6).With the 500 m intervals, the highest correlation appears from 1500 to 2000 m, followed by the below 500 m, the correlation coefficient is 0.66 and 0.64 ($p < 0.001$), respectively. With each 1000 m increase of altitude, precipitation tendency rate increases by 26.9 mm/decade from 1500 to 2000 m and increases by 25 mm/decade below 500 m (Fig. 7). For the 1000 m intervals, the precipitation trend increases significantly with elevation intervals, the highest correlation appears from 2000 to 3000 m. precipitation tendency rate increases by 3.5 mm/decade, 7 mm/decade and 22.1 mm/decade with each 1000 m increase of altitude, and the correlation coefficient is 0.72 ($p < 0.001$), 0.32 ($p < 0.05$) and 0.11 ($p > 0.05$), respectively, but the changes is not significantly above 3000 m (Fig. 8). Furthermore, with the elevation increasing every

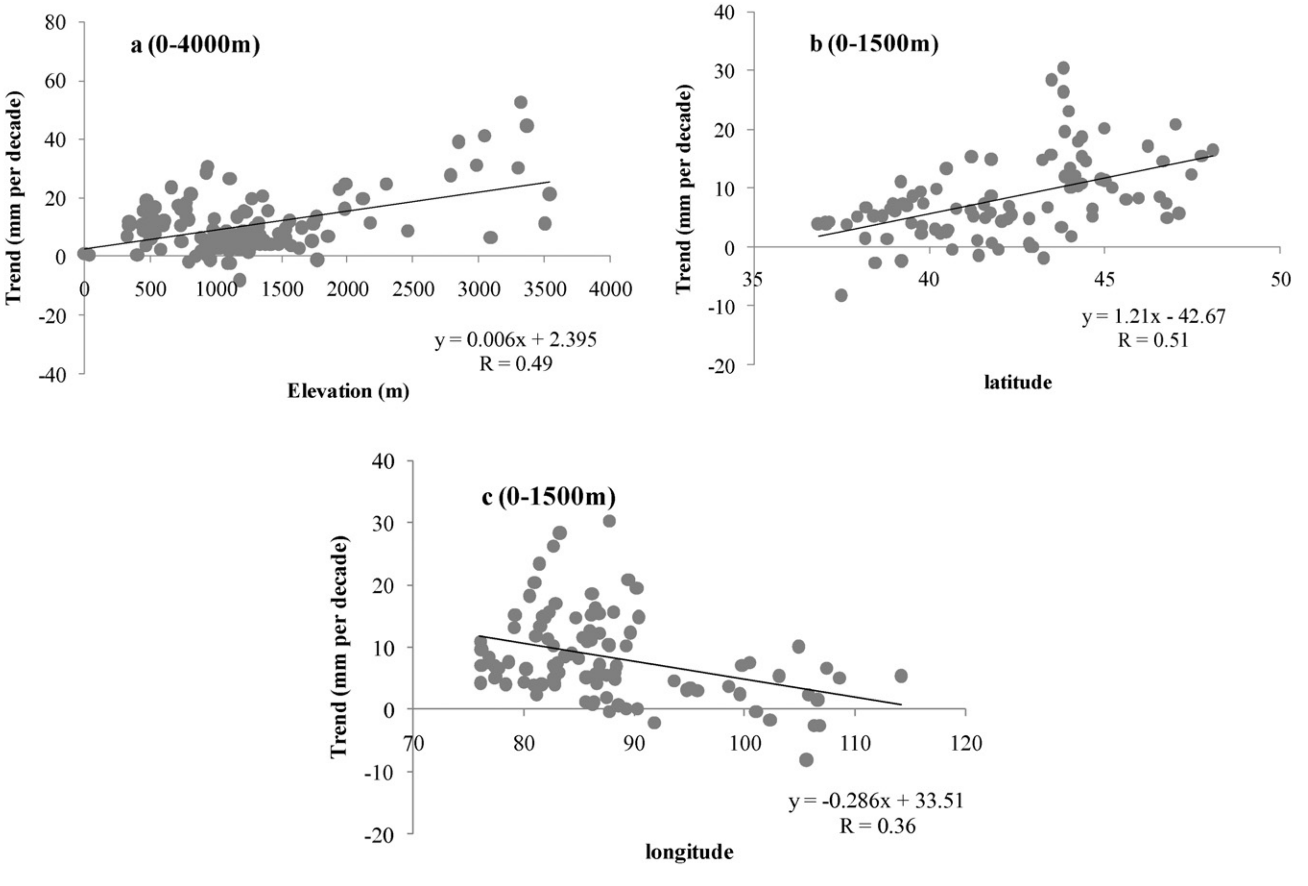

Fig. 5. Trend magnitudes of precipitation (mm/10a) versus elevation (a), latitude (b) and longitude (c) using OLS methods. *R* stands for correlation coefficients for the relationships.

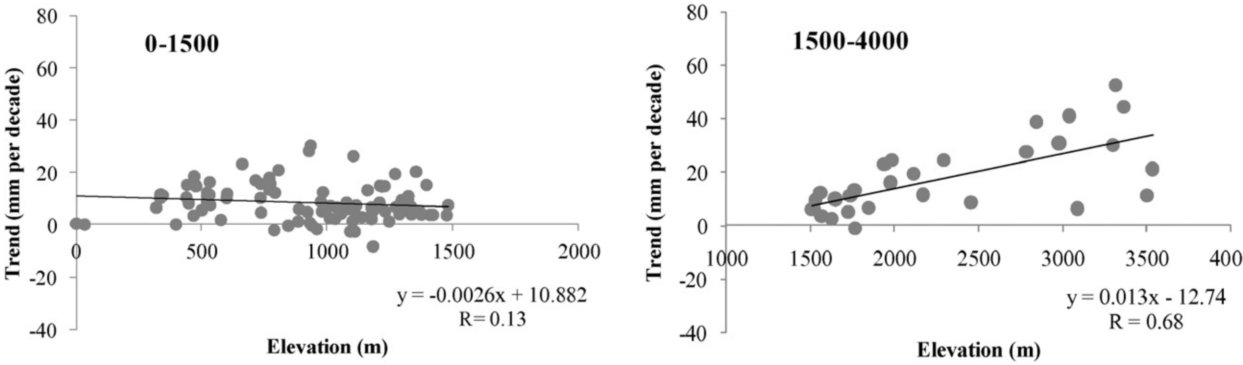

Fig. 6. Trend magnitudes of precipitation (mm/10a) versus elevation by divided at 1500 m using OLS methods. *R* stands for correlation coefficients for the relationships.

1000 m, precipitation tendency rate increases by 10 mm/decade from 2000 to 4000 m.

Fig. 9 shows average wetting trends (mm/decade) for the different periods for stations in 500 m intervals altitudinal bands. Yao et al. (2015a,b) found that the precipitation trend in the mountain areas changed in 1990s, which is consistent with the findings of previous research (Chen et al., 2015; Li et al., 2013; Chen and Xu, 2005). Thus, we divide into two periods, before and after 1990, and uncovered more detailed trends to each. Systematic increases in wetting trend with elevation were revealed for the ATP, as do mean precipitation in spring and autumn (Fig. 9a, b and d). The precipitation trends with elevation were also consistent in spring and autumn before the 1990s, and occurred in summer after the 1990s (Fig.9b, c and d). There was no strong altitudinal effect in other seasons.

It is worth noting that, since these higher mountainous areas are relatively small, the impact of the precipitation change on water resources is severed. The water resources of the ARC strongly depend on the mountainous precipitation and glaciers (snow) meltwater, which is relied on the accumulated snow. The mountain accumulated snow has been influenced by elevation, particularly by the impact of winter precipitation and temperatures trends. Worriedly, although the mountainous precipitation in winter experienced “feebly” increasing in the past 50 years, the impact of the accumulated amount on the glaciers retreat is limited.

4. Discussion

The climate change of the ARC is certainly complex (Chen et al., 2015). It is difficult to accurately uncover the relationship between precipitation trend and elevation only from the short-term, individual point of view. Precipitation trends in ARC are similar to the Northern Hemisphere change over recent 50 years, and exists a wetting center in the Northwest ARC (Wang et al., 2013; Yao et al., 2015a,b). Li et al. (2012) found the increased precipitation mainly at higher altitude areas. In this study, we state that the precipitation trend–elevation relationship in ARC over the past 50 years. There is growing evidence that the elevation-dependent wetting (EDWE), which is the precipitation wetting trend is amplified with elevation. That is to say, the high

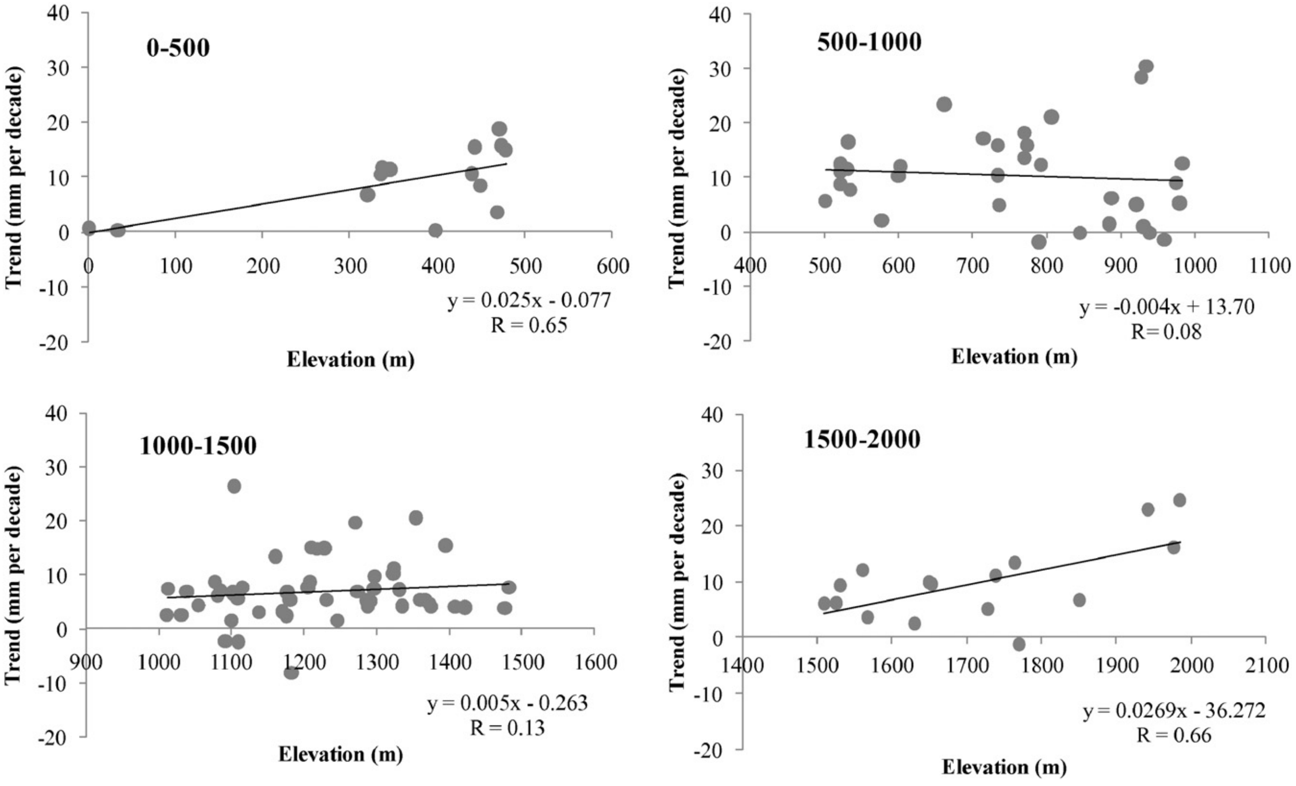

Fig. 7. Trend magnitudes of precipitation (mm/10a) versus elevation with the 500 m intervals using OLS methods. *R* stands for correlation coefficients for the relationships.

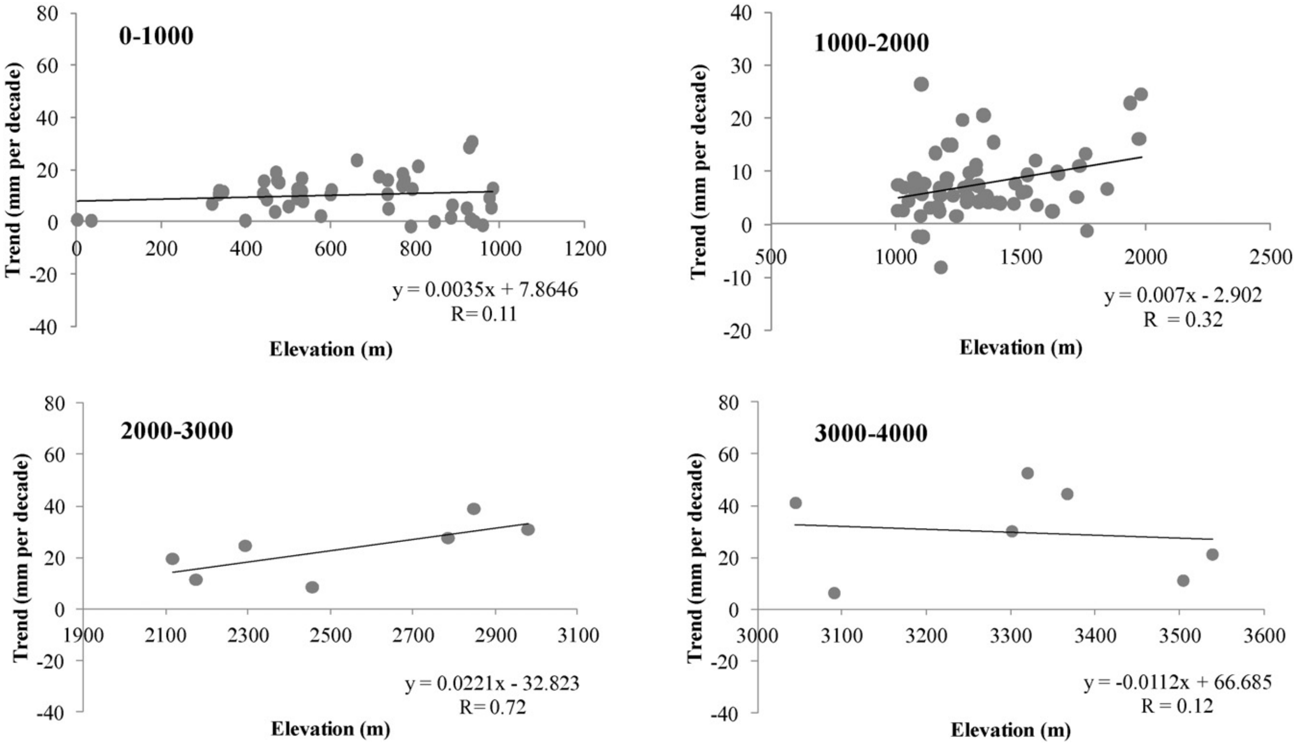

Fig. 8. Trend magnitudes of precipitation (mm/10a) versus elevation with the 1000 m intervals using OLS methods. *R* stands for correlation coefficients for the relationships.

mountainous areas experience more rapid changes in precipitation that areas at lower elevations.

Regional variability in precipitation trends could also be influenced by the large-scale circulation, such as the Tibetan Plateau Index_B (TPI_B), West Pacific Subtropical High (WPSH), North America Subtropical High (NASH) and westerly index (WI), and so on. For instance, it has been found that the Tibetan Plateau affects the atmospheric circulation, it will cause a moisture increase from the Caspian Sea into the ARC, and precipitation may increase in the ARC (Wu et al., 2007; Liu et al., 2007; Bothe et al., 2012; Chen et al., 2014). Li et al. (2016) found that the strengthening of the NASH and WPSH is probably the main factor for the wetting trend in ARC. The increase of NASH, there was enhanced water vapor transported smoothly over the Atlantic to central Asia, associated with precipitation increases significantly by westward flowing wind, especially in the TMA. The stronger WPSH is, the more water vapor transport to the ARC, which is conducive to the East Asian summer monsoon, especially in the QMA (Li et al., 2016).

Based on above-mentioned analysis, we can only consider that there is evidence of the enhanced wetting with elevation of the mountainous areas in ARC. Precipitation change is primarily a response to the water balance, and therefore factors that preferentially increase the water vapor flux and freezing level heights along an elevation gradient would lead to enhanced wetting as a function of elevation. Here we would like to discuss the probability physical mechanisms that have been linked to EDWE. For the arid areas, water vapor is the most important factor for the precipitation changes (Yao et al., 2015a,b). Wentz et al. (2007) further indicated that increased water vapor may increase precipitation. The climatic system is clearly vulnerable in ARC under the effects of weak exchange of water vapor. The uncertainty of mountainous precipitation in was exacerbated by the global change (Chen, 2014b). The water vapor of the mountainous exhibited an increasing trend in ARC, especially in the Northwest ARC and QMA. These water vapor conditions that resulted in these changes have changed markedly (Yao et al., 2015a,b). Fig. 10 shows that the water vapor of the ARC is mainly from westerlies, which brings about abundant warm-wet air from North Atlantic Ocean and Caspian Sea that is likely to sink the atmospheric water vapor and form precipitation when negotiates high mountains (Dai and Wang, 2010; Yao et al., 2015a,b). The water vapor transportation flux field of whole atmosphere exist a high value zone from Northwest ARC and TMA, the center flux value is above 50 g/cm s (Fig. 10). The water vapor of the ARC was mainly provided by the transportation of westerly. E et al. (2009) found that the westerly index directly affects the vapor transportation flux. Westerly index ascending causes water vapor transportation strengthened, more vapors can be brought to arid region of Central Asia, and thus affects the mountainous precipitation.

Elevation-dependent warming (EDW) in mountain regions was identified by the historical observations and model simulations in the world, and reviewed the mechanisms that contribute towards EDW, for example, snow albedo and surface-based feedbacks; water vapor changes and latent heat release; surface water vapor and radiative flux changes; surface heat loss and temperature change; and aerosols (Mountain Research Initiative EDW Working Group, 2015). Dong et al. (2014) further confirmed that the temperature trend increases with elevation from 200 to 2000 m and over 2000 m in China. The annual mean temperature has a systematic increases with elevation on the Tibetan Plateau and northwestern China (Yan and Liu, 2014; Li et al., 2012). In mountainous region, temperature rising strengthens local water circulation faster, and with glacial (snow) meltwater and evaporation enhanced accordingly, improves air humidity and increase water vapor, further promotes the formation of mountain precipitation condition. Bengtsson (1997) has estimated that temperature rising leads to increase atmospheric water vapor by 15% and to increase precipitation by 8%. Schaer et al. (1996) determined that an increase in mean temperature of 2 °C could be accompanied by increases precipitation up to 30% in Alps. On the other hands, enhanced wetting caused by evaporation is expected near the condensation level, which could be further strengthened by higher atmospheric water vapor content resulting from warming (Fig. 11). Temperature and dew-point depression increases causes condensation level rises, then enhanced wetting would occur immediately above the new condensation level, resulting in a significantly greater wetting response at higher elevations (Fig. 11).

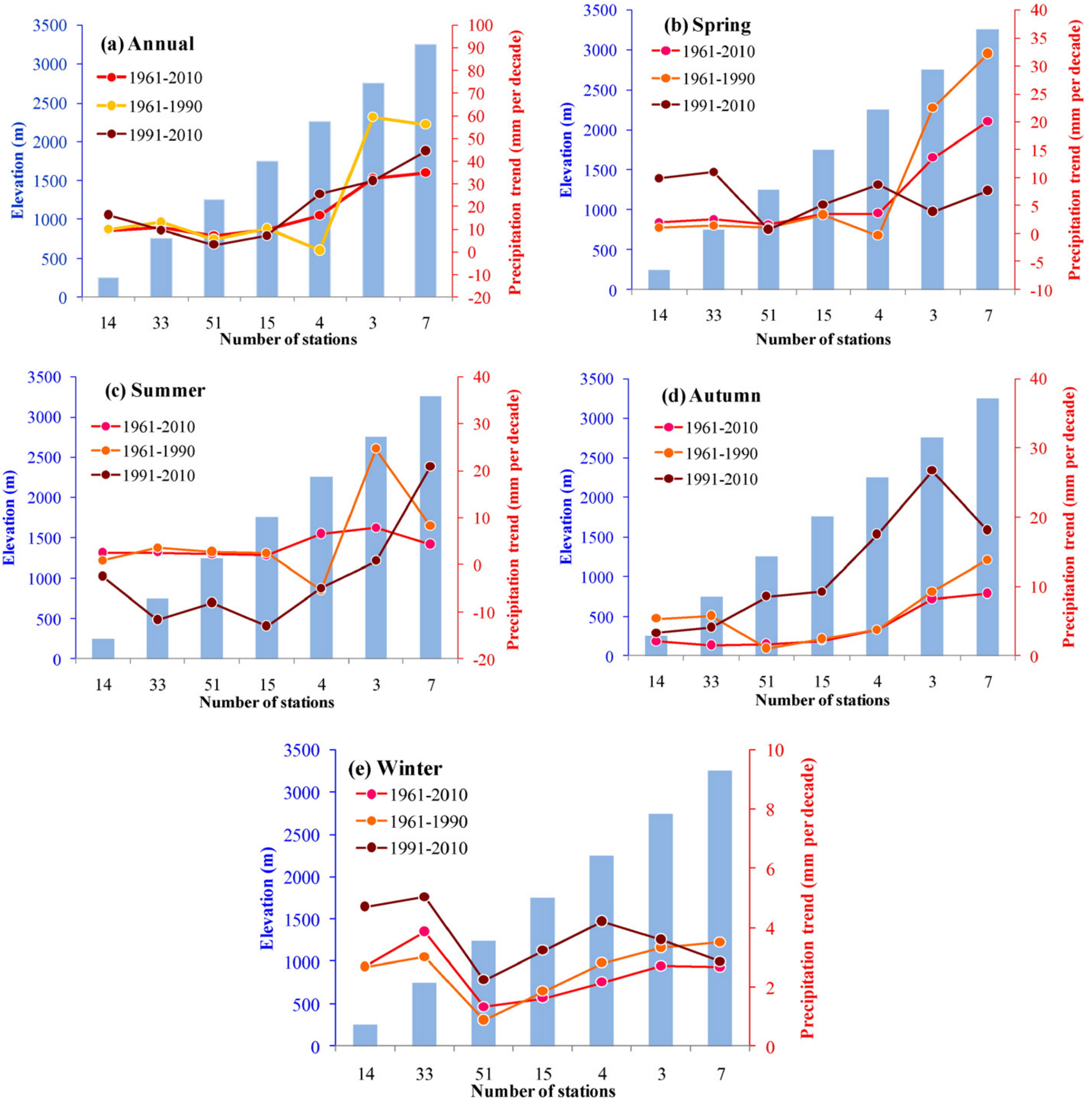

Fig. 9. Elevation- precipitation trends relationship in ARC. a, Annual precipitation trends over 3 time periods. b, c, d, and e are the precipitation trends of Spring, Summer, Autumn and Winter, respectively. Bars represent elevation and trend magnitude is plotted on the y axis according to the 7 elevation ranks of 128 stations. The vertical scale for annual (a) and winter (e) have been adjusted to reflect the more rapid wetting.

In this study, the different relationships between precipitation trend and elevations at different elevation ranges may be the result of combined complex topographical and other local effects. Fig. 7 indicated that the precipitation trend increases was non-significant with elevation from 500 to 1500 m, more significant below 500 m and above 1500 m. This may be due to the fact that human activity (i.e., cities and agricultural activity) is concentrated in the oasis region. These regions experience rapid urbanization, leading to decrease of the soil moisture and increase of anthropogenic aerosols. At the time, the oasis region temperature has been rising faster than that in the mountain region (Li et al., 2013). The heating effect of city leads to the change in precipitation (Chen, 2014b). Furthermore, the irrigation in the oasis region will lead to increases soil moisture, and improves air humidly, which will cause precipitation changes to exhibit relative stability in the oasis region. In addition, temperature rising in the mountain regions can lead to increase the amount of the seasonal glaciers and snow melt and further improves the soil moisture, and promotes water vapor, which lead to the increasing precipitation condition (Li et al., 2013; Chen, 2014b).

There are various uncertainties in the relationship of precipitation wetting trend with elevation in mountainous regions over recent decades. First and foremost, long-term precipitation observed data were extremely sparse at high elevations, especially above 3500 m. For instance, only 2 stations are above 3500 m in ARC. In the Global Historical

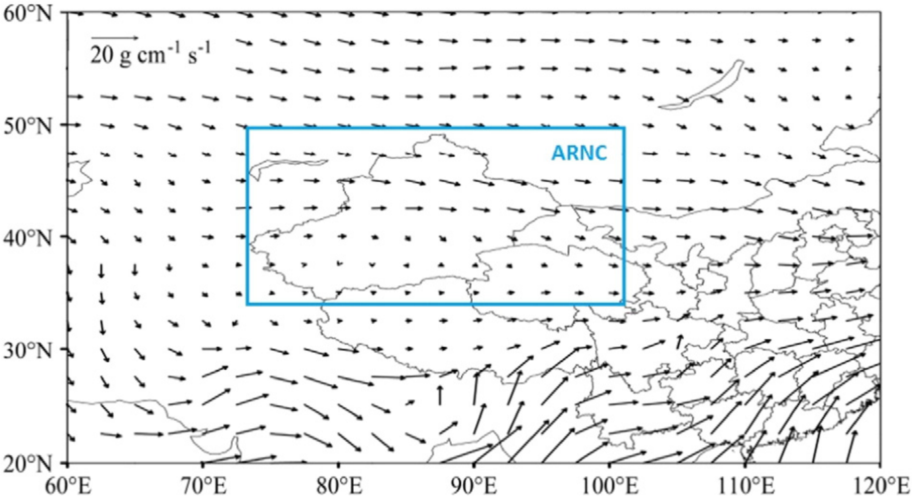

Fig. 10. Average atmosphere water vapor transportation field and flux (g/m s) of 1961–2012 (May–October).

Climatology Network (GHCN), long-term observed data are also nonexistent above 5000 m in mountainous regions of world (Peterson and Vose, 1997; Lawrimore et al., 2011). The satellite products, atmospheric reanalysis or model simulations can also provided the precipitation data, but these datasets have limitations. Furthermore, there has been a lack of consistency in the observation instrument and environments, such as vegetation changes, human grazing and relocation of stations. Therefore, these uncertainties would effects the EDWE results to a certain extent, and should be further observed and investigated in future studies. To fully investigate the phenomenon of EDWE, more precipitation observations at stations are essential but many high elevations regions (generally, above 4000 m) are still poorly. Mountain Research Initiative (MRI, 2015) appeal to integrate the observational network, which combines three main approaches are surface in-situ climate observations, satellite data and high-resolution climatic modeling. The surface in-situ network needs to fill the higher elevations regions observational gap, and to include more water cycle key variables, such as humidity, water vapor, snowfall and clouds. Moreover, the high-resolution palaeoclimate datasets may be needed to extract the precipitation signal and to understand the EDWE.

5. Conclusion

In the present study, monthly precipitation data at 128 meteorological stations selected from the arid regions of the China (ARC) during 1961–2012. We investigated that the precipitation trend–elevation relationship in ARC. It is found that the annual total precipitation (ATP) showing a significant wetting trend and the wetting station reaches the 93.8%. Spatially, the highest magnitudes of wetting in the mountainous area, the Qilian Mountainous Area (QMA) had the highest wetting rate of 38.7 mm/decade, followed by the Tianshan Mountainous Area (TMA) and Altai Mountainous Area (AMA).

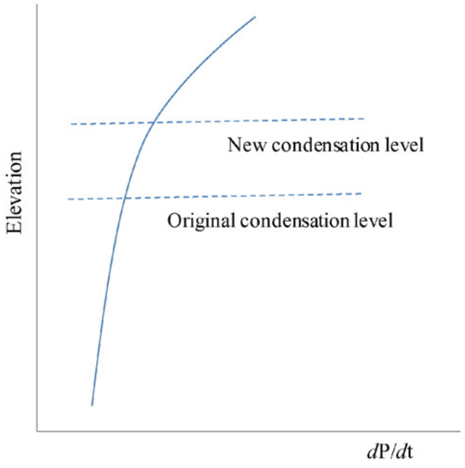

Fig. 11. Schematic of the relative vertical profile of the wetting rates and elevations. The x axis represents the rate of wetting (dT/dt or expected trend magnitude).

We can consider that there is evidence of the elevation-dependent wetting (EDWE), which is the precipitation wetting trend is amplified with elevation. The precipitation trend increases significantly with elevation except for the altitude from 500 to 1500 m, the highest correlation appears above 1500 m, increases by 13 mm/decade with each 1000 m. With the elevation increasing every 1000 m, precipitation tendency rate increases by 7 mm/decade from 1000 to 2000 m and increases by 10 mm/decade from 2000 to 4000 m.

EDWE has an impact on the change of the cryospheric systems, ecosystems and water resources, especially in arid regions of China. We discuss mechanisms that contribute towards EDWE: water vapor changes and warming-driven water circulation speeds up. We propose future needs to increase evidence of understand the EDWE in other mountainous regions, and its controlling mechanisms through integrated the observational network of surface in-situ climate observations, satellite data and high-resolution climatic modeling.

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