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Short Communication

Does summer precipitation trend over and around the Tibetan Plateau depend on elevation?

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ABSTRACT: The Tibetan Plateau (TP) experienced a rapid warming and wetting in recent decades. The elevation dependence of warming rate has been established, while the question of trend in precipitation against the elevation gradient remains open. By using the *in situ* observation of precipitation, air temperature, and surface specific humidity from 91 stations over and around the TP, this study investigated how the trends in summer precipitation varied along the elevation gradient over and around the TP during the period 1970–2014. The major findings are as follows: (1) the trends in summer precipitation from 1970 to 2014 displayed an increasing tendency at a rate of 0.83% decade^{-1} km^{-1} with the increased elevation, and the rate for 1991–2014 (2.23% decade^{-1} km^{-1}) is even greater and (2) the temporal trends in surface air temperature, surface specific humidity (surface water vapour) from *in situ* observations and total column of water vapour from Japanese 55-year reanalysis (JRA-55) data over most stations consistently display similar elevation dependence, which provides a plausible explanation for the elevation dependence of the summer precipitation trends based on the Clausius–Clapeyron relationship. The large-scale atmospheric circulations are other possible factors influencing the elevation dependence of summer precipitation trends, which needs further investigations.

KEY WORDS elevation dependence; summer precipitation; temporal trends; the Tibetan Plateau

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1. Introduction

Precipitation is the main sources of water at Earth's surface, and is essential to life on Earth. The global warming (Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5), 2013) caused a series of changes, including precipitation and evapotranspiration, especially in the mountainous regions (Yang *et al.*, 2011a, 2011b; Li *et al.*, 2014). Many studies in the past have identified and quantified elevation-dependent warming (EDW), with a strong evidence pointing to more rapid warming at higher elevations (Qin *et al.*, 2009; Pepin *et al.*, 2015). While the changes in surface air temperature would lead to increased water vapour according to the Clausius–Clapeyron relationship (Dai, 2006; Trenberth, 2011), and have an impact on global precipitation (Wentz *et al.*, 2007) under the assumption of constant relative humidity, regional changes in precipitation also depends on other factors such as atmospheric circulation (Marvel and Bonfils, 2013) and air pollution (Gong *et al.*, 2007). Particularly, how the EDW will affect precipitation at different heights remains to be investigated.

Previous studies mainly focused on the relationship between the altitudes and precipitation itself in present and future across the globe (Giorgi *et al.*, 1997; Kang *et al.*, 1999; Brunsdon *et al.*, 2001; Kim, 2001; Kim *et al.*, 2002; Gouvas *et al.*, 2009; Kotlarski *et al.*, 2012), especially in the mountain regions. Generally, these studies found an increasing amount of precipitation with altitude up to the highest elevations of the mountain or an elevation below the top, above which precipitation amounts did not increase any more. With the amplification of EDW in high elevations, researchers started to pay more attention to the precipitation trends along the elevation gradients around the world (Rowe *et al.*, 2008; Im and Ahn, 2011; Arakawa and Kitoh, 2012; Beusekom *et al.*, 2015). However, the current studies based on observations are limited and some of these studies focused on model simulated results (Arakawa and Kitoh, 2012).

Evidence for elevation-dependent climate changes has come from several sources including *in situ* data, satellite data, atmospheric reanalysis data, or model (general circulation model or regional climate model; GCM or

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RCM) outputs. However, these sources all have their shortcomings. Satellite data have relatively short time duration (Qin *et al.*, 2009) and their performances are subjected to a variety of errors and uncertainties in mountain areas (Tong *et al.*, 2014). Atmospheric reanalysis data sets are generally not suitable for trend analysis due to their inhomogeneity features (Thorne and Vose, 2010). GCM or RCM models generally have poor performance due to coarse spatial resolution and poor performance for precipitation (Mueller and Seneviratne, 2014), especially in the high-elevation regions (Duan *et al.*, 2013; Gao *et al.*, 2015a, 2015b). The *in situ* observational data from rain gauges, despite of their limitation such as being sparse in the high-elevation regions, are still the best and most reliable source of information for assessment of the elevation-dependent changes.

The Tibetan Plateau (TP) has an average elevation of over 4000 m ASL (above sea level) and an area of about 2.5×10^6 km^2, known as 'the Roof of the world'. As one of the most elevated regions in the world, the TP has obvious climate change including cryospheric changes in the recent years, as well as the significant EDW phenomenon (Kang *et al.*, 2010; Yang *et al.*, 2011a, 2011b; You *et al.*, 2014, 2015, 2016). Because global warming brought more precipitation in the world over the past two decades (Wentz *et al.*, 2007), it is hypothesized that there would be elevation dependence of precipitation changes induced by the EDW found over this region. Studies on elevation dependence of precipitation changes are important for impact assessments including those on the glaciological dynamics and hydrological cycles in the high-elevation regions of the TP. To the best of our knowledge, there are no published studies that examined the relationship between trends in summer precipitation and elevations over the TP by using *in situ* data, although the elevation dependence of trend in precipitation were investigated by model simulations (Arakawa and Kitoh, 2012).

This study focused on exploring the elevation dependence of trends in summer precipitation over and around the TP for the period 1970–2014, using a database covering 91 ground based stations from China Meteorological Administration (CMA). The objective was to determine whether the elevation-dependent phenomenon in summer precipitation trends could be detected over and around the TP against the background of EDW. The paper is structured as the follows. Section 2 briefly describes the study region, followed by a description of the data and methodology. Section 3 presents the results of elevation dependence of trend in the summer precipitation and a discussion about its possible reasons. The conclusion and discussion are given in Section 4.

2. Materials and methods

The TP in western China (26°–40°N, 78°–105°E) was selected as the study region. The study region is the highest and largest highland in the world and exerts a great influence on regional and global climate and environment (Wu *et al.*, 2005; Wu *et al.*, 2007; Yao *et al.*, 2007, 2012). The TP has been experiencing an overall rapid wetting and warming in recent years (Liu and Chen, 2000; Niu *et al.*, 2004; Yang *et al.*, 2011a, 2011b; Chen *et al.*, 2015) and an interesting EDW phenomenon (Qin *et al.*, 2009; Pepin *et al.*, 2015). These phenomena are assumed to influence the hydrologic cycle and its elements, especially against the elevation due to a larger span of elevation over and around the TP (Guo *et al.*, 2015, 2016). The topography over and around the TP was described in Figure 1(a) using the digital elevation model from the shuttle radar topography mission (http://srtm.usgs.gov), which generally decreases from northwest to southeast.

The *in situ* station data from the National Meteorological Information Center of the CMA (http://cdc.cma.gov.cn/) were used in this study, including precipitation, surface specific humidity, and air temperature (2 m). There are 91 stations which have continuous data over the period (1970–2014). The selected stations have elevations above 1000 m ASL and the data used include surface air temperature, surface specific humidity, and precipitation in summer (June-July-August). The spatial distribution of the 91 stations is shown in Figure 1(a). The distribution of the stations is uneven and very sparse in the western TP and relatively dense in the eastern TP. The distribution of the stations against altitude is shown in Figure 1(c). The total column of water vapour, archived at the National Center for Atmospheric Research, was derived from the Japanese 55-year reanalysis data (hereafter JRA-55) produced by Japan Meteorological Agency/Japan (Kobayashi *et al.*, 2015). This reanalysis has been proven to have a good performance over the TP (Chen *et al.*, 2014).

The linear regression method shown below was adopted in this study to calculate the linear trends for all variables used in the study,

$$y = ax + b. \tag{1}$$

where, y denotes the summer values from air temperature, surface specific humidity, and precipitation, x represents the time (here years), a is the slope, i.e. the linear trends, and b is the intercept. The statistical significance of the trends determined was evaluated using the Student's t-test as follows:

$$t = r\left((n-2)/\left(1-r^2\right)\right)^{1/2}. \tag{2}$$

The elevation-dependent phenomenon was revealed not only in the whole period 1970–2014, but also in 1970–1990 and 1991–2014, supported by an abrupt change point detection method. Figure S1(a), Supporting information, shows the summer mean air temperature and its linear trend in two periods (1970–1990 and 1991–2014). It was found that the temperature was significantly increased around and after 1990s (with a trend of 0.49 °C decade^{-1}), and kept stable variations with a small trend value (0.09 °C decade^{-1}) before 1990. The abrupt point detection method also finds that the cumulative anomaly value reaches the lowest point around 1990s (Figure S1(b)). So, in our study we selected two periods (1970–1990 and 1991–2014) to compare the

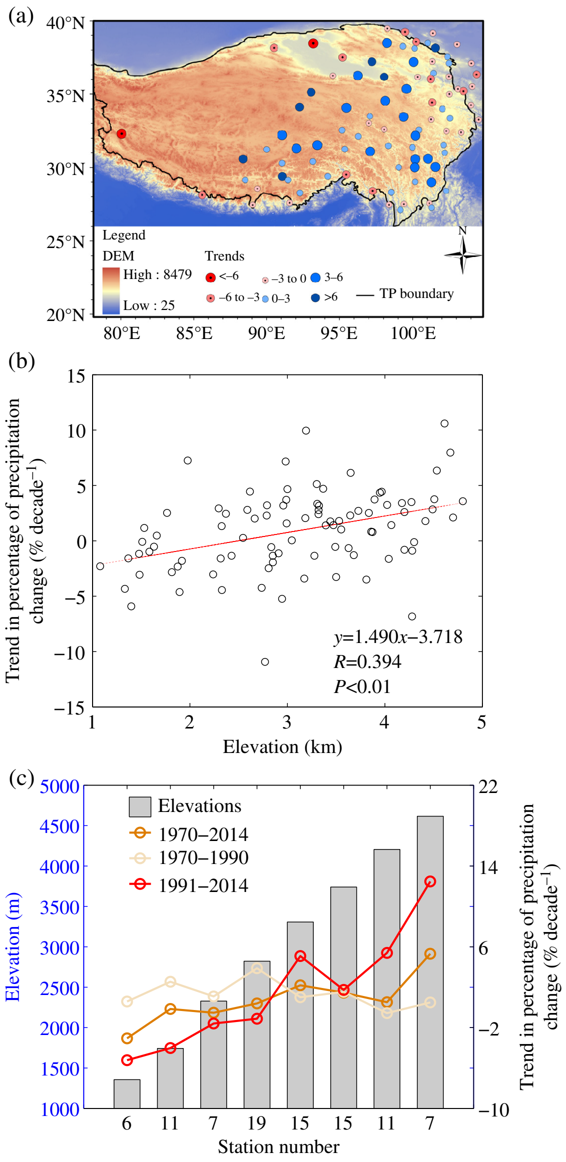

Figure 1. Spatial distribution of long-term (1970–2014) trends in percentage of precipitation changes (% decade^{-1}) (a), scatter plot of trends (% decade^{-1}) against elevation (km) (b), and elevation dependence of trends (% decade^{-1}) over three time periods (1970–1990, 1991–2014, and 1970–2014) (c) in summer over and around the TP. The numbers in horizontal axis in (c) represent the stations in each elevation band. R and P represent the correlation coefficient between trends and elevations and the confidence level, respectively.

elevation-dependent phenomenon over the TP. The similar classification method was also used by Pepin *et al.* (2015).

3. Results

Since the beginning of the 1980s, the TP has experienced an overall surface air warming and moistening (Yang *et al.*, 2011a, 2011b, 2014; Chen *et al.*, 2015). The relative trends, better to describe the relative changes of precipitation, were calculated by calculating the linear trends divided by the mean precipitation during the period 1971–2000. Figure 1(a) shows the long-term (1970–2014) relative trends of the summer precipitation during the period 1970–2014. It was found that most of the stations experienced obvious increasing trends, while some stations in the northwest and southern part of TP had decreasing trends, which is consistent with previous studies (Yang *et al.*, 2011a, 2011b, 2014). Interestingly, it is noted that stations in the high-elevation ranges showed faster increase of the summer precipitation than those in the low-elevation ranges and some stations in the low elevations had decreasing trends in the summer precipitation. The scatter plot (Figure 1(b)) of the relative trends against elevations reveals strong elevation dependence, as indicated by a high correlation coefficient of 0.39 which is statistically significant at the 99% confidence level.

To investigate the sensitivity of elevation dependence to different periods, the variations of the trends in the summer precipitation (% decade^{-1}) with the increases of elevation in 500-m wide altitudinal bands starting at 1000 m ASL were explored for the period 1970–1990, 1991–2014, and 1970–2014, respectively (shown in Figure 1(c)). It is found that the summer precipitation trends present different characteristics with the increasing of elevation during the three periods. The trends in the summer precipitation had an obvious increasing tendency along the elevation gradient for 1970–2014. However, there was no elevation dependence found for 1970–1990, while a distinct increasing trend against elevation gradient appeared in the period 1991–2014, with a significant rate of 2.23% decade^{-1} km^{-1} at the 95% confidence level along with elevation. This dependence is much larger than that for 1970–2014 (0.83% decade^{-1} km^{-1}).

According to the Clausius–Clapeyron relationship, higher temperature could produce higher evaporation, hold more water vapour, and lead to more precipitation. If other conditions are the same, air temperature can act as a driving factor for precipitation changes. The winter warming rate over the TP is the largest, fall has the next highest warming rate, while the summer and spring show relatively less warming (Liu and Chen, 2000; You *et al.*, 2007; Liu *et al.*, 2009; Qin *et al.*, 2009; Pepin *et al.*, 2015). During the period 1970–2014, nearly all the stations experienced warming in summer (Figure 2(a)), especially in the northeast and central parts of TP, where the elevations are relatively high. Furthermore, the strong elevation dependence in warming appeared in summer with a correlation efficient of 0.56 which is statistically significant at the 99% confidence level (Figure 2(b)). Consistent increases of the warming rates along an elevation gradient were found (Figure 2(c)) during the three periods (1970–2014, 1970–1990, and 1991–2014), although the strengths of the elevation dependence differ in different periods. During the period 1991–2014, the elevation dependence (with a rate of 0.15 °C decade^{-1} km^{-1}) is stronger than those in 1970–2014 and 1970–1990. The results are consistent with the previous research (Pepin *et al.*, 2015).

The water vapour has a positive feedback on surface temperature (Hansen *et al.*, 1984; Dai, 2006; You *et al.*, 2015). Thus, it is expected that a significant EDW can cause an elevation dependence of water vapour changes. Figure 3(a)

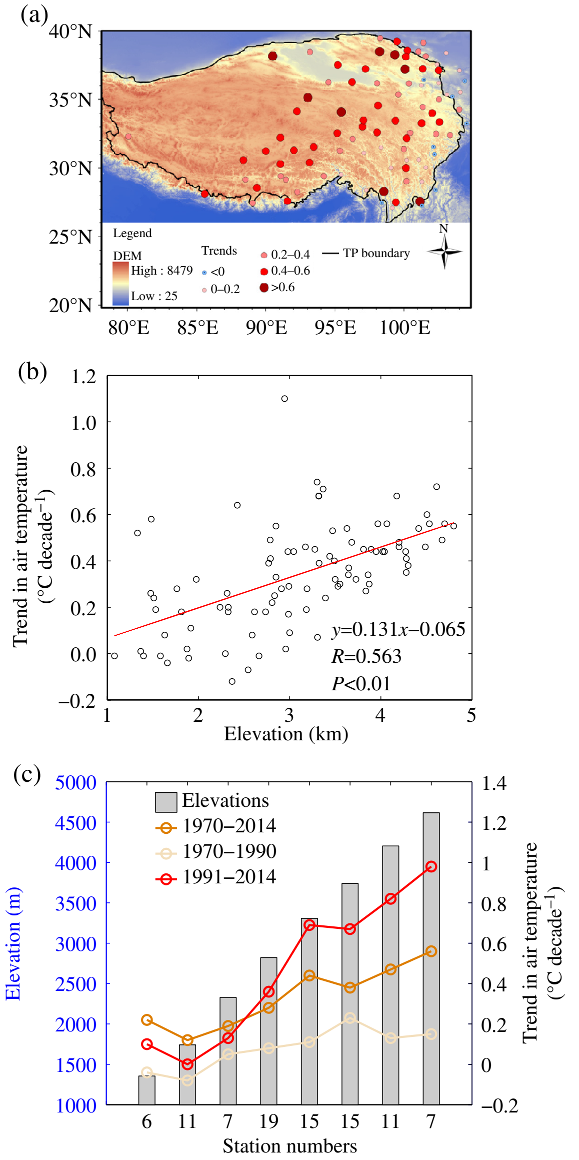

Figure 2. Similar to Figure 1, but for air temperature (°C decade^{-1}).

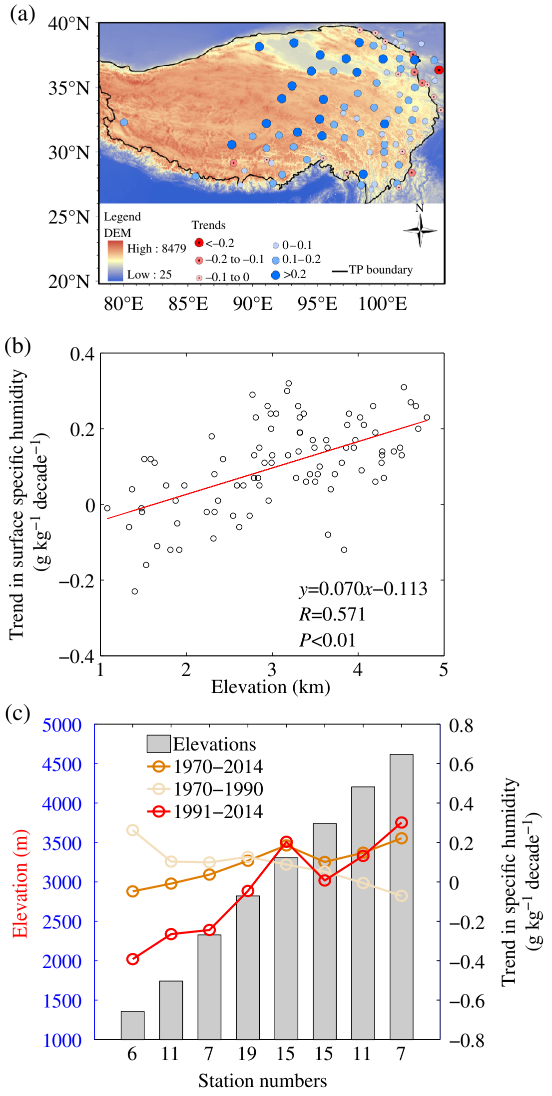

Figure 3. Similar to Figure 1, but for surface specific humidity (g kg^{-1} decade^{-1}).

shows the spatial distribution of long-term (1970–2014) trends in surface specific humidity in summer season. Surface specific humidity was increased at nearly all stations of the TP, especially in the higher elevations. The scatter plot (Figure 3(b)) between the trends of surface specific humidity and elevations displays strong elevation dependence with a correlation coefficient of 0.57 which is statistically significant at the 99% confidence level, and in 1991–2014 the trends of surface specific humidity have stronger elevation dependence than those in the other two periods (1970–2014, and 1970–1990) (Figure 3(c)). The similar phenomena were observed for surface water vapour pressure (not shown here), due to a significant correlation between water vapour pressure and specific humidity with a correlation coefficient of 0.95 which is significant at the 99% confidence level. The results above showed that the trends of temperature, surface specific humidity displayed a consistent elevation-dependent phenomenon as with precipitation. In other words, the elevation dependence of warming has most likely induced the elevation dependence of increasing trend in surface water vapour through a positive feedback mechanism, because the changes of surface specific humidity are largely controlled by surface temperature (Dai, 2006).

In order to reveal the changes of total water vapour in the column, the total water vapour in the column from JRA-55 reanalysis data was used. The JRA-55 reanalysis data used an operational data assimilation system to produce a high-quality homogeneous data set. As many observations as possible are collected, including those used in past operational systems and delayed observations as well as digitized observations. In particular, the JRA-55 also assimilated all observations (e.g. Global Positioning System (GPS) water vapour measurements) from the JICA (Japan International Cooperation Agency) programme, which makes the JRA-55 reanalysis most fit to our study. It was found that the total water vapour in the column from JRA-55 are consistently increasing over and around the TP, especially in the northern part of the TP

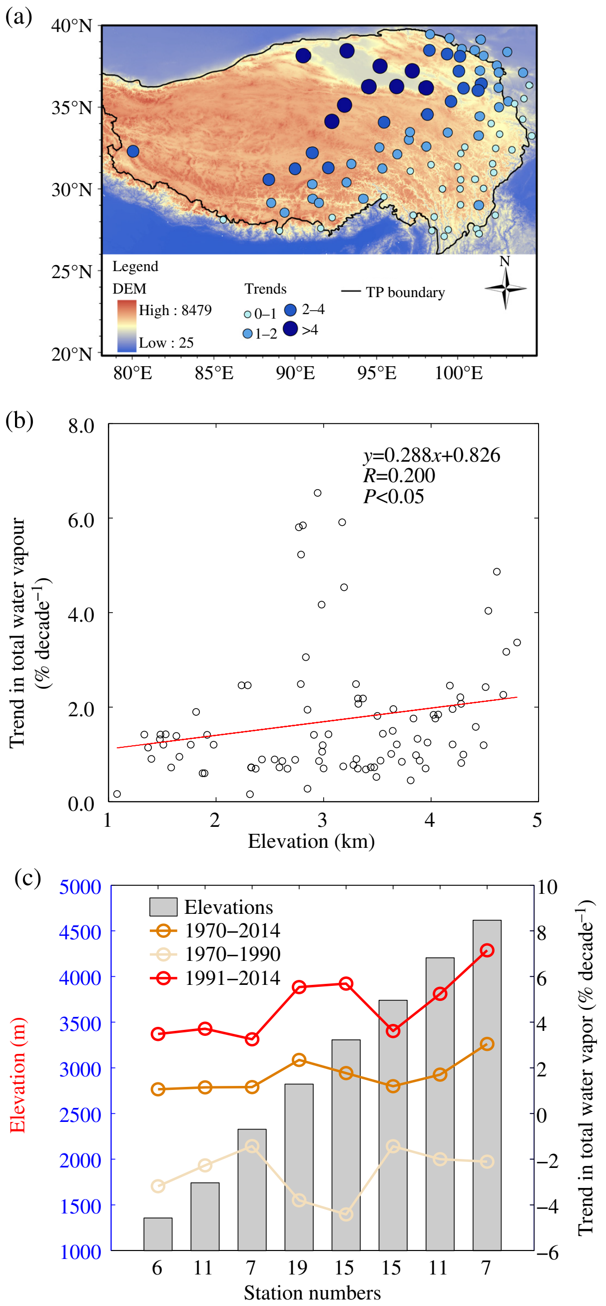

Figure 4. Similar to Figure 1, but for the percentage of total water vapour changes from JRA-55 reanalysis data. The point values are derived from the gridded JRA-55 reanalysis data based on 91 stations. The unit of trend is % decade^{-1}.

(Figure 4(a)), well corresponding to the regions with larger warming rate. The trends in station values derived from the gridded JRA-55 reanalysis data have elevation dependence with a correlation coefficient of 0.20, being significant at the 95% confidence level (Figure 4(b)). Similarly, stronger elevation dependence is also found in the period 1991–2014, followed by a rate of 0.410% decade^{-1} km^{-1} against elevation (Figure 4(c)). The elevation dependence of precipitable water trends is at least one of the main influencing factors for the elevation dependence of precipitation trends over and around the TP.

Over all, most of the stations over the TP experienced warming and wetting, especially with larger temporal variability in the central-east parts of TP, where higher elevations exist. According to the Clausius–Clapeyron relationship, the EDW could have caused the elevation dependence of surface water vapour and total water vapour in the column, which gave rise to an elevation dependence of summer precipitation during the period 1970–2014, especially significantly for 1991–2014. In other words, the changes in summer precipitation can be accounted for by changes in summer temperature based on the Clausius–Clapeyron relationship, which is different from the results by Rangwala *et al.* (2009).

In addition, the precipitation can be influenced by the large-scale atmospheric circulation systems. The TP in summer is mainly influenced by the Indian monsoon and East Asian monsoon (Yao *et al.*, 2012), especially for low-elevation stations at the eastern and southern margins of TP. Both of the monsoons have become weaker over the last decades (Cowan and Cai, 2011; Yao *et al.*, 2012), and higher-elevation environments experienced greater changes in surface wind speed than lower-elevation regions (Guo *et al.*, 2016). Therefore, low-elevation stations at the eastern and southern margins of the TP experience smaller changes of precipitation in 1991–2014 than in 1970–1990. However, higher-elevation stations in the interior of TP, dominated by greater wind reductions (Guo *et al.*, 2016), have less moisture loss, which possibly caused larger changes of precipitation in high-elevation stations than in low-elevation stations. All these lead to more significant elevation dependence for summer precipitation changes in 1991–2014 than in 1970–1990.

Another possible factor for precipitation changes is from the influence of aerosols, which is helpful to condense of water vapour and to promote occurrence of precipitation over the TP (Lau *et al.*, 2006, 2010). Recent studies found that higher concentration of aerosols in the Himalayas and the northern parts around the Qaidam Basin (Bonasoni *et al.*, 2010; Xu *et al.*, 2015). However, because of few observations and short time-coverage, there has been little systematic investigation of the elevation signal of aerosols (including anthropogenic pollutants) in mountain regions (Pepin *et al.*, 2015), including the TP. The relationship between aerosols and elevations and the influence of aerosols on precipitation over the TP needs further investigations.

4. Conclusions and discussions

Monthly *in situ* precipitation data from 91 stations were used to identify the elevation dependence of trend in summer precipitation over and around the TP during the period 1970–2014. The majority of the stations showed increasing trends except for the stations in the northeastern and southern parts. A significant elevation dependence of the summer precipitation trends, which shows an increasing precipitation trend with elevation, was found over and around the TP during the period 1970–2014. The dependence became stronger during the period 1991–2014 compared with that during the period 1970–1990.

The identified elevation dependence of the summer precipitation trends is in line with the increasing trends of temperature with elevation. It was shown that the temperature dependence also got stronger during the period 1991–2014 compared with that during the period 1970–1990. The warmer air can hold more water vapour on the basis of the Clausius–Clapeyron relationship, which makes it more likely to generate more precipitation. The surface water vapour (surface specific humidity) from the 91 stations and the total water vapour in the atmosphere over and around the TP from the JRA-55 reanalysis data did show a consistent increasing trend and stronger elevation dependence in 1991–2014 than previous period. The temperature, water vapour, and precipitation in summer displayed consistent increasing trends and elevation dependences over most stations of the TP, especially after 1990s. In addition, the large-scale atmospheric circulations may also influence the elevation dependence of summer precipitation trend, which needs further investigation.

All stations used in the study are located over and around the TP above 1000 m. In order to test the sensitivity of elevation dependence to selections of station, the comparisons are shown between stations above 2000 m and those above 3000 m (shown in Figure S2). The trends in air temperature have significant elevation dependence consistently for stations from 2000 to 3000 m. This phenomenon happens for trends in summer precipitation and surface specific humidity, but not significant for stations above 3000 m. For the total water vapour in the column, the elevation dependence appeared for stations above 2000 and 3000 m, although not significant at the 95% confidence level. The possible reason is the total water vapour data from JRA with a low resolution (1.25°) cannot describe the actual variation of total water vapour along with the elevation over this complex terrain.

The findings of this study come with a number of caveats. Firstly, the stations used are sparse and some parts of the TP such as western part were not represented by the existing observational network, which limited the quality of the estimations. Although, there are several other sources of information available from gridded data sets, satellite measurement, and reanalysis products, rain gauge data as used in this study is still considered the most reliable and relevant source of information for this study. Secondly, only few *in situ* observations were available above the 5000 m. Given the higher elevation of many mountain tops in the TP, the validity of our results for high elevations needs to be further investigated. Thirdly, there were several stations where the temperature, surface water vapour, and precipitation in summer displayed different variability compared with the majority of the stations. Most of these stations were distributed at the margin of the TP. Thus, the Clausius–Clapeyron relationship alone could not explain all these different changes and relationship, which was consistent with the results by Rangwala *et al.* (2009). In other words, the changes in surface specific humidity could not be accounted for entirely by changes in temperature based on the Clausius–Clapeyron relationship, and future studies should examine other relevant physical processes.

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Supporting information

The following supporting information is available as part of the online article:

Figure S1. Time series of summer mean air temperature (°C) and its linear trend in periods 1970–1990 and 1991–2014 (a); time series of cumulative departure values of summer air temperature (°C) in the period 1970–2014 (b). The summer mean air temperature is averaged from 91 stations. The fitted equations in two periods are shown in the (a).

Figure S2. Elevation dependence of trends in summer air temperature (°C decade^{-1}), precipitation (% decade^{-1}), specific humidity (g kg^{-1} decade^{-1}) and total water vapour (% decade^{-1}) for the period of 1970–2014 over and around the TP based on 74 stations over 2000 m (a)–(d) and 49 stations over 3000 m (e)–(h).

References

Arakawa O, Kitoh A. 2012. Elevation dependency of summertime precipitation and its change by global warming over the Tibetan Plateau and the surroundings simulated by 1 60-km-mesh Atmospheric General Circulation Model. *J. Meteorol. Soc. Jpn.* **90A**: 151–165.

Beusekom AE, González G, Rivera MM. 2015. Short-term precipitation and temperature trends along an elevation gradient in Northeastern Puerto Rico. *Earth Interact.* **19**(3): 1–33.

Bonasoni P, Laj P, Marinoni A, Sprenger M, Angelini F, Arduini J, Bonafe U, Calzolari F, Colombo T, Decesari S, Di Biagio C, di Sarra AG, Evangelisti F, Duchi R, Facchini MC, Fuzzi S, Gobbi GP, Maione M, Panday A, Roccato F, Sellegri K, Venzac H, Verza GP, Villani P, Vuillermoz E, Cristofanelli P. 2010. Atmospheric brown clouds in the Himalayas: first two years of continuous observations at the Nepal-Climate Observatory-Pyramid (5079 m). *Atmos. Chem. Phys.* **10**(15): 4823–4885.

Brunsdon C, McClatchey J, Unwin DJ. 2001. Spatial variations in the average rainfall-altitude relationship in Great Britain: an approach using geographically weighted regression. *Int. J. Climatol.* **21**(4): 455–466.

Chen G, Iwasaki T, Qin H, Sha W. 2014. Evaluation of the warm-season diurnal variability over East Asia in recent reanalyses JRA-55, ERA-interim, NCEP CFSR, and NASA MERRA. *J. Clim.* **27**(14): 5517–5537.

Chen D, Xu B, Yao T, Guo Z, Cui P, Chen F, Zhang R, Zhang X, Zhang Y, Fan J, Hou Z, Zhang T. 2015. Assessment of past, present and future environmental changes on the Tibetan Plateau. *Chin Sci Bull*, **60**(32): 3025–3035, doi: 10.1360/N972014-01370 (in Chinese with English abstract).

Cowan T, Cai W. 2011. The impact of Asian and non-Asian anthropogenic aerosols on 20th century Asian summer monsoon. *Geophys. Res. Lett.* **38**(11): L11703–L11707.

Dai A. 2006. Recent climatology, variability, and trends in global surface humidity. *J. Clim.* **19**(15): 3589–3606.

Duan AM, Hu J, Xiao ZX. 2013. The Tibetan Plateau summer monsoon in the CMIP5 simulations. *J. Clim.* **26**(19): 7747–7766.

Gao Y, Leung R, Zhang Y, Lan C. 2015a. Changes in moisture flux over the Tibetan Plateau during 1979-2011: insights from the high resolution simulation. *J. Clim.* **28**(10): 4185–4197.

Gao Y, Xu J, Chen D. 2015b. Evaluation of WRF mesoscale climate simulations over the Tibetan Plateau during 1979-2011. *J. Clim.* **28**(7): 2823–2841.

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

Gong KW, Zhao W, Li N, Barajas B, Kleinman M, Sioutas C, Horvath S, Lusis AJ, Nel A, Araujo JA. 2007. Air-pollutant chemicals and oxidized lipids exhibit genome-wide synergistic effects on endothelial cells. *Genome Biol.* **8**(7): R149.

Gouvas M, Sakellariou N, Xystrakis F. 2009. The relationship between altitude of meteorological stations and average monthly and annual precipitation. *Stud. Geophys. Geod.* **53**(4): 557–570.

Guo XY, Wang L, Tian LD. 2015. Spatial-temporal variability of vertical gradients of major meteorological observations around the Tibetan Plateau. *Int. J. Climatol.* **36**(4): 1901–1916.

Guo XY, Wang L, Tian LD, Li XP. 2016. Elevation-dependent reductions in wind speed over and around the Tibetan Plateau. *Int. J. Climatol.* **36**, doi: 10.1002/joc.4727.

Hansen J, Lacis A, Rind D, Russell G, Stone P, Fung I, Ruedy R, Lerner J. 1984. Climate sensitivity: Analysis of feedback mechanisms. In *Climate Processes and Climate Sensitivity*, Hansen JE, Takahashi T (eds). AGU Geophysical Monograph 29, Maurice Ewing Vol. 5. American Geophysical Union, 130–163.

Im ES, Ahn JB. 2011. On the elevation dependency of present-day climate and future change over Korea from a high resolution regional climate simulation. *J. Meteorol. Soc. Jpn.* **89**(1): 89–100.

Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5). 2013. Summary for Policymakers: The Physical Science Basis, Contribution of Working Group I to the IPCC Fifth Assessment Report Climate Change. http://www.climatechange2013.Org/images/upload/WGIAR5-SPM&uscore;Approved27Sep2013.pdf (accessed 27 September 2013).

Kang ES, Cheng GD, Lan YC, Jin HJ. 1999. A model for simulating the responses of runoff from the mountainous watersheds of inland river basins in the arid area of northwest China to climatic changes. *Sci. China Ser. D: Earth Sci.* **D42**(suppl 1): 52–63.

Kang S, Xu Y, You Q, Wolfgang-Albert F, Pepin N, Yao T. 2010. Review of climate and cryospheric change in the Tibetan Plateau. *Environ. Res. Lett.* **5**(1): 015101 (8pp).

Kim J. 2001. A nested modeling study of elevation-dependent climate change signals in California induced by increased atmospheric CO2. *Geophys. Res. Lett.* **28**(15): 2951–2954.

Kim J, Kim TK, Arritt RW, Miller NL. 2002. Impacts of increased atmospheric CO2 on the hydroclimate of the Western United States. *J. Clim.* **15**(14): 1926–1942.

Kobayashi S, Ota Y, Harada Y, Ebita A, Moriya M, Onoda H, Onogi K, Kamahori H, Kobayashi C, Endo H, Miyaoka K, Takahashi K. 2015. The JRA-55 reanalysis: general specifications and basic characteristics. *J. Meteorol. Soc. Jpn.* **93**(1): 5–48.

Kotlarski S, Bosshard T, Lüthi D, Pall P, Schär C. 2012. Elevation gradients of European climate change in the regional climate model COSMO-CLM. *Clim. Change* **112**(2): 189–215.

Lau KM, Kim MK, Kim KM. 2006. Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. *Clim. Dyn.* **26**(7): 855–864.

Lau KM, Kim MK, Kim KM, Lee WS. 2010. Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols. *Environ. Res. Lett.* **5**(2): 302–307, doi: 10.1088/1748-9326/5/2/025204.

Li X, Wang L, Chen D, Yang K, Wang A. 2014. Seasonal evapotranspiration changes (1983–2006) of four large basins on the Tibetan Plateau. *J. Geophys. Res. Atmos.* **119**(23): 13079–13095.

Liu X, Chen B. 2000. Climatic warming in the Tibetan Plateau during recent decades. *Int. J. Climatol.* **20**(14): 1729–1742.

Liu XD, Cheng ZG, Yan LB, Yin ZY. 2009. Elevation dependency of recent and future minimum surface air temperature trends in the Tibetan Plateau and its surroundings. *Glob. Planet Change* **68**(3): 164–174.

Marvel K, Bonfils C. 2013. Identifying external influences on global precipitation. *Proc. Natl. Acad. Sci.* **110**(48): 19301–19306.

Mueller B, Seneviratne SI. 2014. Systematic land climate and evapotranspiration biases in CMIP5 simulations. *Geophys. Res. Lett.* **41**(1): 128–134.

Niu T, Chen LX, Zhou ZJ. 2004. The characteristics of climate change over the Tibetan Plateau in the last 40 years and the detection of climatic jumps. *Adv. Atmos. Sci.* **21**(2): 193–203.

Pepin NC, Bradley RS, Diaz HF, Baraer M, Caceres EB, Forsythe N, Fowler H, Greenwood G, Hashmi MZ, Liu XD, Miller JR, Ning L, Ohmura A, Palazzi E, Rangwala I, Schöner W, Severskiy I, Shahgedanova M, Wang MB, Williamson SN, Yang DQ. 2015. Elevation-dependent warming in mountain regions of the world. *Nat. Clim. Change* **5**(5): 424–430.

Qin J, Yang K, Liang S, Guo X. 2009. The altitudinal dependence of recent rapid warming over the Tibetan Plateau. *Clim. Change* **97**(1–2): 321–327.

Rangwala I, Miller JR, Xu M. 2009. Warming in the Tibetan Plateau: possible influences of the changes in surface water vapor. *Geophys. Res. Lett.* **36**(6): L06703, doi: 10.1029/2009GL037245.

Rowe AK, Rutledge SA, Lang TJ, Ciesielski PE, Saleeby SM. 2008. Elevation-dependent trends in precipitation observed during NAME. *Mon. Weather Rev.* **136**(12): 4962–4979.

Thorne PW, Vose RS. 2010. Reanalysis suitable for characterizing long-term trends: are they really achievable? *Bull. Am. Meteorol. Soc.* **91**(3): 353–361.

Tong K, Su FG, Yang DY, Hao ZC. 2014. Evaluation of satellite precipitation retrievals and their potential utilities in hydrologic modeling over the Tibetan Plateau. *J. Hydrol.* **519**(A): 423–437.

Trenberth KE. 2011. Changes in precipitation with climate change. *Clim. Res.* **47**(47): 12–138.

Wentz FJ, Ricciardulli L, Hilburn K, Mears C. 2007. How much more rain will global warming bring? *Science* **317**(5835): 233–235.

Wu SH, Yin YH, Zheng D, Yang QY. 2005. Climatic trends over the Tibetan Plateau during 1971–2000. *J. Geogr. Sci.* **17**(2): 141–151.

Wu G, Liu Y, Zhang Q, Duan A, Wang T, Wan R, Liu X, Li W, Wang Z, Liang X. 2007. The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. *J. Hydrometeorol.* **8**(4): 770–789.

Xu C, Ma YM, You C, Zhu ZK. 2015. The regional distribution characteristics of aerosol optical depth over the Tibetan Plateau. *Atmos. Chem. Phys.* **15**(11): 12065–12078.

Yang K, Ye B, Zhou D, Wu B, Foken T, Qin J, Zhou Z. 2011a. Response of hydrological cycle to recent climate changes in the Tibetan Plateau. *Clim. Change* **109**(3–4): 517–534.

Yang Q, Ma Z, Chen L. 2011b. A preliminary analysis of the relationship between precipitation variation trends and altitude in China. *Atmos Oceanic Sci Lett* **4**(1): 41–46.

Yang K, Wu H, Qin J, Lin C, Tang W, Chen Y. 2014. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. *Glob. Planet Change* **112**: 79–91.

Yao T, Pu J, Lu A, Wang Y, Yu W. 2007. Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding regions. *Arct. Antarct. Alp. Res.* **39**(4): 642–650.

Yao T, Thompson L, Yang W, Yu W, Gao Y, Guo X, Yang X, Duan K, Zhao H, Xu B, Pu J, Lu A, Xiang Y, Kattel DB, Joswiak D. 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Change* **2**(9): 663–667.

You Q, Kang S, Wu Y, Yan Y. 2007. Climate change over the Yarlung Zangbo River Basin during 1961–2005. *J. Geogr. Sci.* **17**(4): 409–420.

You Q, Fraedrich K, Min J, Kang S, Zhu X, Pepin N, Zhang L. 2014. Observed surface wind speed in the Tibetan Plateau since 1980 and its physical causes. *Int. J. Climatol.* **34**(6): 1873–1882.

You Q, Min J, Lin H, Pepin N, Sillanpää M, Kang S. 2015. Observed climatology and trend in relative humidity in the central and eastern Tibetan Plateau. *J. Geophys. Res. Atmos.* **120**(9): 3610–3621.

You Q, Jiang Z, Bao Y, Pepin N, Fraedrich K. 2016. Trends in upper tropospheric water vapour over the Tibetan Plateau from remote sensing. *Int. J. Climatol.* **36**(15): 4862–4872, doi: 10.1002/joc.4674.