Variability of the precipitation over the Tianshan Mountains, Central Asia. Part II: Multi-decadal precipitation trends and their association with atmospheric circulation in both the winter and summer seasons

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Abstract
The annual precipitation over the Tianshan Mountains experienced an inter-decadal transition shift towards an increasing trend in the late 1980s. This study conducts attribution analysis from atmospheric circulation factors based on the Global Precipitation Climatology Centre (GPCC) dataset and NCEP/NACR reanalysis data. The results show that (a) Winter precipitation in the Tianshan Mountains is affected by multi-decadal oscillations with periods of 26.8 and 44.7 years, and has entered a period of positive anomalies after 1988. Although the non-linear trend of winter precipitation in the Tianshan Mountains firstly increased and then decreased after 1979, the multi-decadal fluctuation of precipitation caused the Tianshan Mountains in winter to be in a wet period from the 1980s until 2011. (b) We find that the East Atlantic-West Russia (EATL/WRUS) teleconnection pattern has a similar multi-decadal variability as Tianshan precipitation in winter. The wet period of Tianshan in winter after 1988 is mainly due to the enhanced meridional feature of the EATL/WRUS triggering more water vapour flux from low-latitude oceanic areas. (c) Summer precipitation in the Tianshan Mountains has an obvious multi-decadal scale of 33.5 years and shows a non-linear growth trend. Tianshan Mountains in summer entered a humid period after 1986. (d) The Scandinavia (SCAND) teleconnection pattern represents important circulation variability affecting Tianshan summer precipitation. The vigorous high pressure over the Ural Mountains and the low pressure over Central Asia during the SCAND negative phase in summer jointly lead to enhanced moisture transport from the Arctic Ocean to the Tianshan Mountains. (e) Apart from SCAND, the Silk Road pattern (SRP) and East Asia-Pacific teleconnection (EAP) also impacted Tianshan summer precipitation during the periods 1964–1984 and 1985–2004.
1 INTRODUCTION

Located in the hinterland of Eurasia and far from the sea, Central Asia is one of the most arid regions in the mid-latitudes (Bernauer and Siegfried, 2012). In arid Central Asia the highest mountain range is the Tianshan, which stretches over 2,500 km and has high peaks up to 7,439 m (Scheffel Richard and Wernet, 1980). As a giant catchment area, the Tianshan Mountains are the main water source for Central Asia. The local precipitation generated by the Tianshan topography plays a key role in shaping the diverse climatic features of Central Asia (Aizen et al., 1997). Previous studies simulating the effect on precipitation in Central Asia after removing the Tianshan Mountains found that without the Tianshan, there is a significant decrease in glacial recharge by solid precipitation and continued glacier shrinking will eventually lead to a decrease in glacial recharge by solid precipitation and thus total runoff (Sorg et al., 2012; Chen et al., 2020; Zhang et al., 2020). This is detrimental to the spatial distribution of water resources in Central Asia. A deeper understanding of precipitation variability in the Tianshan Mountains and of the associated large-scale atmospheric processes is essential for predicting water resource changes in the Tianshan as well as Central Asia. In Part I (Guan et al., under review, Part I of the presented study, hereafter Part I) we analyse in detail the long-term trends and their multi-time scale characteristics of annual and seasonal precipitation in the Tianshan Mountains. This provides the basis for studying atmospheric teleconnection drivers of precipitation variability in the Tianshan Mountains in Part II.

Located in the westerly wind belt, mid-latitude westerlies control precipitation in the Tianshan Mountains. The position and strength of the westerly jet affect moisture fluxes originating from the Atlantic Ocean, the Mediterranean, and the high latitudes directed towards Central Asia and the Tianshan Mountains (Schiemann et al., 2008). Particularly, the uplift of westerly air masses in the Tianshan Mountains over its high mountain barriers results in high amounts of topographically induced precipitation (Aizen et al., 1995; Chen et al., 2016). Bothe et al. (2012) illustrated that different positions of the westerly flow are largely responsible for the amount of winter precipitation over the Tianshan Mountains. Links between large-scale wave patterns and Tianshan precipitation are usually studied by calculating the correlations between precipitation data and climate indices. There are many different findings on the effects of the large-scale circulation teleconnections on precipitation in the different parts of the Tianshan. A significant correlation coefficient has been found between Arctic Oscillation (AO) and precipitation extremes in winter time in the eastern Tianshan Mountains (Wang et al., 2013). Water

KEYWORDS
East Asia-Pacific teleconnection (EAP), East Atlantic-West Russia pattern (EATL/WRUS), precipitation, Scandinavia pattern (SCAND), Silk Road pattern (SRP), Tianshan Mountains
vapour content in the southern Tianshan Mountains (Yao et al., 2013). Chen et al. (2013) suggested that dry periods occurring in the western Tianshan are linked to the winter North Atlantic Oscillation (NAO). However, Zhong et al. (2017) found that NAO was almost not correlated with annual precipitation in eastern Tianshan. They also concluded that the impacts of AO on eastern Tianshan precipitation were weak and locally confined. According to the correlation analysis, the two Eurasian (EU) patterns, the East Atlantic-West Russia (EATL/WRUS) and the Scandinavian (SCAND) have the most pronounced influence on regional precipitation (Bothe et al., 2012). Gerlitz et al. (2018) also stated that EATL/WRUS and SCAND patterns have the strongest influence on the regional circulation over Central Asia with enhanced westerly winds prevailing during their positive phases. Besides Northern Hemispheric wave tracks, the links between tropical circulation and precipitation in the Tianshan Mountains are of relevance. An et al. (2020) found that the Indian Summer Monsoon (ISM), El Niño–Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO) are positively correlated with precipitation along the northern and southern slopes of the Chinese Tianshan. Zhong et al. (2017) stated that annual precipitation over eastern Tianshan is more strongly related to ISM than ENSO. ISM and precipitation have a positive correlation in nearly the whole Chinese Tianshan but have a negative correlation with precipitation along the southern slopes of the Chinese Tianshan during the dry season (Zhong et al., 2017).

Most of the above studies on the relationship between atmospheric circulation and precipitation in the Tianshan Mountains address the interannual scale (Bothe et al., 2012; Chen et al., 2013; Zhong et al., 2017). Although some studies have explored the relationship between precipitation and atmospheric circulation in the Tianshan on multi-timescales, these have only focused on parts of the Tianshan Mountains (An et al., 2020). There is a lack of studies examining the relationship between precipitation and atmospheric circulation across the entire Tianshan Mountains on multi-timescales. According to Part I, in addition to the non-linear long-term trend of precipitation, there are also multi-decadal scale oscillations in the Tianshan Mountains. Therefore, based on the regional division of the Tianshan Mountains and the study of precipitation variations in Part I, Part II pays specific attention to the analysis of impacts of atmospheric circulation patterns on the multi-decadal variability of precipitation in the Tianshan Mountains. Although winter precipitation only accounts for a small amount of annual precipitation in the entire Tianshan, the main form of winter precipitation in the Tianshan is snowfall which has a profound effect on the formation of the Tianshan snow cover. The multi-scale variability of winter precipitation and its response to atmospheric circulation is therefore also worth investigating. Therefore, we have analysed the multi-scale characteristics of Tianshan precipitation in winter and summer and how these are influenced by atmospheric circulation in chapters 3.1 and 3.2, respectively. The results of this study are expected to provide guidance for managing regional water resources and ecosystems to adapt to changes in precipitation associated with these atmospheric circulation patterns.

2 STUDY AREA, DATA, AND METHODS

2.1 Study area

Located in Central Asia, the Tianshan Mountains extend approximately 2,450 km from west to east with an average width of 400 km (Figure 1). The Tianshan Mountain’s highest peak reaches 7,439 m. Located within the largest continent on Earth, and far away from the ocean, the Tianshan is characterized by a pronounced continental climate. However, this continental climate is modulated by the elevation and topography of the mountain ranges (Aizen et al., 1995; Aizen et al., 1997). The sub-Tianshan has its own climate characteristics. The reader is referred to Part I for the delineation of the sub-Tianshan regions.

Bounded by Lake Issyk, the area west of Lake Issyk is the Western Tianshan. The Western Tianshan is affected by the interaction of anti-cyclones over Siberia and to a greater extent by the southwestern cyclonic circulation during the cold season. Consequently, precipitation occurs primarily during winter and spring (Aizen et al., 1995). In summer the Western Tianshan is mainly controlled by subtropical anti-cyclones resulting in a precipitation minimum during that season. Located to the north of Lake Issyk and the south bank of Ili Valley is Northern Tianshan. Northern Tianshan is affected by the strong Siberian anti-cyclones, resulting in little precipitation in winter. Precipitation mainly during spring and summer is caused by the development of frontal cyclones (Aizen et al., 1995; Chen et al., 2017). In the Ili Valley, water vapour advected from the west is forced to rise and condense due to orographic uplift. The “trumpet” of Illi Valley shaped by Zailiyskiy Alatau and Borokonu Mountains make the Ili Valley one of the areas with maximum amounts of precipitation, as well as the area with the most extreme precipitation events in the Northern Tianshan Mountains (Hu, 2004).

South of the Ili Valley lies Central Tianshan. The Tianshan mountain range forms a barrier that prevents transport of water vapour into Central Tianshan areas,
which results in little precipitation there, especially in winter. During summer, relatively humid and cold air from the west, coupled with the development of convection, and more unstable atmospheric stratification, triggers maximum precipitation in June and July (Chen et al., 2016). Finally, there is Eastern Tianshan, which bounded by the cities of Urumqi and Dabancheng in China. It is the most remote and the least influenced region with respect to the East Asian monsoon and westerly circulation. Therefore, Eastern Tianshan receives the least precipitation of the entire region (Wei et al., 2003), with annual precipitation sums of about 100 mm (Chen et al., 2016; Part I).

2.2 | Data

Monthly precipitation used in this study was obtained from the Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2018). The Full Data Monthly Product V.2018 (V.8) was constructed from quality-controlled observations from 75,100 to 79,200 stations (Schneider et al., 2018). This dataset provides monthly precipitation at high spatial resolution (0.25°) for the period 1901–2016 and is available at https://www.dwd.de/EN/ourservices/gpcc/gpcc.html. In this study we used data for the period 1950 to 2016.

The NCEP/NCAR Reanalysis data (Kalnay et al., 1996) was used for the circulation and water vapour transport analysis. NCEP/NCAR reanalysis data has 2.5° x 2.5° horizontal resolution and 17 levels of vertical resolution (from the surface to 10 hPa) (Kalnay et al., 1996). The data are available at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html. In this study we use 500, and 200 hPa monthly means geopotential heights, specific humidity, and U-wind and V-wind components provided by NCEP/NCAR are used to calculate the integrated water vapour content and water vapour flux.

We use atmospheric indices to investigate the influence of circulation anomalies of key atmospheric systems on precipitation in the Tianshan Mountains. The indices of North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Pacific-North American (PNA), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), East Atlantic (EA), Scandinavia (SCAND), West Pacific (WP), East Pacific/North Pacific (EP/NP), El Niño–Southern Oscillation (ENSO), Southern Oscillation Index (SOI), East Atlantic-West Russia Pattern (EATL/WRUS), and Multivariate ENSO Index (MEI) are available from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA), USA (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml). The Dipole Mode Index (DMI), which represents the intensity of the Indian Ocean Dipole is from Physical Sciences Laboratory, NOAA, USA (https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/index.html). The Indian Monsoon (ISM) index, and Webster and Yang Monsoon (WYM) Index are downloaded from Asia-Pacific Data-Research Center, the University of Hawai`i at Mānoa (http://apdrc.soest.hawaii.edu/projects/monsoon/definition.html).

2.3 | Method

2.3.1 | Ensemble empirical mode decomposition (EEMD)

In this study the ensemble empirical mode decomposition (EEMD) method is applied to extract the multi-
period oscillations and non-linear trend of Tianshan precipitation (Huang et al., 1998; Wu and Huang, 2009). A non-linear and non-stationary series can be decomposed into a series of inherent mode functions (IMF) and a residual using the EEMD method. The first IMF represents the highest frequency oscillation and the frequencies of the following IMF decrease in turn (Wu et al., 2007; Wu and Huang, 2009). The decadal signals with periods of more than 20 years are treated as multi-decadal variability (MDV). The definition of the decadal signals in this study can be found in section 2.3.2 in Part I. Meanwhile, the residual is regarded as the long-term non-linear trend. A detailed description of the EEMD method can be found in Wu and Huang (2009) and the specific EEMD decomposition steps are documented in Part I.

2.3.2 | Calculations of total precipitable water vapour and water vapour flux

We use total precipitable water vapour content (PWC) and water vapour flux to describe the spatial distribution of water vapour and characteristics of water vapour transport. The PWC can be defined by (Benton et al., 1950) as

\[
PWC = -\frac{1}{g} \int_{p_1}^{p_t} qdp
\]

The vertically integrated zonal \((Q_z)\) and meridional \((Q_\varphi)\) water vapour transports can be expressed as:

\[
Q_z = -\frac{1}{g} \int_{p_1}^{p_t} uqdp
\]

and

\[
Q_\varphi = -\frac{1}{g} \int_{p_1}^{p_t} vqdp
\]

Here, \(g\) is gravitational acceleration, \(p_1\) is surface pressure, the Tianshan is a huge terrain object. Its surface pressure has to be taken into account. Therefore, the integral calculations have started with the surface pressure, having already removed the pressure below the surface pressure. \(p_1\) is the pressure at the top of troposphere, and \(q\) is specific humidity. \(u\) and \(v\) are the zonal and meridional wind components, respectively.

Relationships between precipitation time series and atmospheric indices are studied through correlation analysis (Chatfield, 1980). Furthermore, regression patterns derived by regressing the 500 hPa and 200 hPa geopotential height anomaly fields as well as 700 hPa wind anomaly field onto the precipitation anomaly are applied to reveal the spatial relation of atmospheric circulation and Tianshan precipitation (Thompson and Wallace, 1998). We used the Student's \(t\) test (Hald, 1952) to assess statistical significance in the correlation and regression analyses.

3 | RESULTS

3.1 | Atmospheric circulation anomaly and the variability of winter precipitation

The average winter precipitation (December, January, and February) in the entire Tianshan Mountains is 44 mm, and the lowest amount of precipitation in all seasons. According to the results of Part I, winter precipitation accounts for 17.4% of the annual precipitation. Precipitation in winter is extremely unevenly distributed throughout the Tianshan Mountains. The average winter precipitation is only 13 mm in the Central Tianshan but reaches 98 mm in the Western Tianshan.

It can be seen from Table 1 that there is no obvious correlation between Tianshan winter precipitation and atmospheric indices except for a significantly positive correlation with EATL/WRUS. The correlation coefficient between the two is 0.42 and statistically significant at the 99% confidence level indicating that EATL/WRUS is an important atmospheric circulation feature affecting the interannual variation of Tianshan winter precipitation.

The regression patterns of the 500 hPa geopotential height anomaly and the 700 hPa horizontal wind anomaly to Tianshan winter precipitation anomaly show that there is a teleconnection wave from Northern Europe to Central Asia, and to East Asia (Figure 2). The three-centre west–east pattern with the western centre in Northern Europe (“A” in Figure 2), an oppositely signed centre located in the northeast of the Caspian Sea and southwest of Russia (“B” in Figure 2), and a centre with a sign like that of Northern Europe in Northeast China and Korea (“C1” in Figure 2). This structure precisely reflects the EATL/WRUS pattern (Barnston and Livezey, 1987). Furthermore, a centre of positive height-­anomalies is found in Northern India at 70°–80°E, 25°–35°N ("C2" in Figure 2). Tianshan is located exactly between the abnormal cyclonic circulation in Central Asia and the abnormal anticyclonic circulation in Northern India. The strong anomalous pressure gradient between the negative height anomalies on the north and the positive height anomalies on the south induce strong westerly and southwesterly winds (Figure 2), advecting water vapour from Eurasia and the Arabian Sea, thereby contributing...
to the increase of winter precipitation in the Tianshan Mountains.

In order to more precisely explain the influence of this pattern on the Tianshan winter precipitation, we define a modified EATL/WRUS index. According to the calculation of the EATL/WRUS atmospheric teleconnection index as provided by previous studies (Barnston and Livezey, 1987), the index is defined as a linear combination of several abnormal centres of geopotential height. Therefore, $H_{\text{index}}$ in our study is defined as the linear combination of the standardized geopotential height of the four areas indicated in Figure 2: A (10°–30°E, 55°–65°N), B (70°–90°E, 45°–60°N), C1 (120°–140°E, 30°–40°N), and C2 (70°–80°E, 25°–35°N) to

$$H_{\text{index}} = \frac{1}{4}H_A + \frac{1}{4}H_C - \frac{1}{2}H_B \quad (4)$$

$H_A$, $H_B$, and $H_C$ are the average normalized geopotential heights of $A$, $B$, and $C$ ($C1 + C2$). $H_{\text{index}}$ and the monthly EATL/WRUS index provided by NOAA show consistent variations (Figure 3). The correlation coefficient between the two is 0.49, and is significant at the 99% confidence level. Therefore, $H_{\text{index}}$ can be considered to characterize the features of EATL/WRUS related to precipitation in the Tianshan Mountains. As shown in Figure 3 the standardized $H_{\text{index}}$ strongly relates to Tianshan winter precipitation variation from 1950 to 2016 ($r = 0.60$ at 99% confidence level). EATL/WRUS index by NOAA is based on the definition from Barnston and Livezey (1987) which defined the positive phase of EATL/WRUS as associated with positive height anomalies located over Europe and Northern China, and negative height anomalies located over the Central North Atlantic and north of the Caspian Sea. According to this definition, the positive height-anomaly centred over Northern India at 70°–80°E, 25°–35°N that we describe as “C2” in Figure 2 is not captured. The $H_{\text{index}}$ instead takes this active centre over India into account, and thus more fully explains the MDV of Tianshan winter precipitation. The abnormal precipitation in winter 1968/69 has a strong relationship with $H_{\text{index}}$. This strong consistency is not reflected in the original EATL/WRUS record provided by NOAA (Figure 3). Hence, the positive height-anomaly centred over Northern India might have been an important factor jointly with the EATL/WRUS to trigger the strong positive anomaly of precipitation specifically in the winter 1968/69. Therefore, not only the four main centres of action located over Europe, Northern China, the Caspian Sea, and Central North Atlantic are important to Tianshan winter precipitation but also the anomaly centred over Northern India is a factor of relevant influence.

Winter precipitation series in Tianshan Mountains during 1950–2016 were decomposed into oscillation
periods of 3.6, 6.7, 13.4, and multi-decadal variabilities with periods of 44.7 years (Figure S1; see Part I for details). It can be seen from MDV in Figure 4 that winter precipitation in the Tianshan Mountains was in a dry period before 1988, and in a humid period from 1989 to 2013 (Figure 4). The long-term trend shows a non-linear characteristic of first increasing and then, after 1979, decreasing tendency. Due to the impact of observed MDV characteristics, the long-term trend of precipitation (trend curve in Figure 4) is still not sufficient to change that precipitation remained in a humid phase from 1988 to 2010 as can be seen in the curve representing the combined effect of MDV and trend (black “MDV + Trend” line in Figure 4).

Since $H_{\text{index}}$ represents the EATL/WRUS pattern very well (Figure 3), we used it in the following analysis: MDV of $H_{\text{index}}$ shows a shift in 1988 (Figure 4). The long-term trend also shows non-linear characteristics of first increasing and then, after 1996, decreasing tendency. $H_{\text{index}}$ MDV superimposed on the non-linear trend results in a negative period of $H_{\text{index}}$ before 1988 and a positive period from 1989 to 2014.

Due to the shift of MDV of the Tianshan winter precipitation and EATL/WRUS in 1988 (Figure 4), the difference of circulation in the two periods 1950–1988 (period 1) and 1989–2016 (period 2) are compared. The regression pattern of the 500 hPa geopotential height anomaly with respect to the Tianshan winter precipitation anomaly in both periods reveals obvious EATL/WRUS pattern characteristics (Figure 5). However, in period 2, the zonal feature of the EATL/WRUS weakened, and the meridian feature strengthened (Figure 5b). The low-pressure centre moved westward over the Caspian Sea, while the oppositely signed centre originally over northwestern India moved eastward. Meanwhile, the low-latitude area is controlled by high pressure and its intensity is larger than that in period 1. The Tianshan is located between the cyclone and the anticyclone in both periods. The cyclone and the anticyclone in period 1 are on the north and south of the Tianshan Mountains, respectively (Figure 5a). In period 2, these two centres are on the west and southeast of the Tianshan Mountains enhancing the southwestward airflow from lower latitudes between the two pressure systems (Figure 5b). Thus, this feature enhances advection of water vapour from the south, which is conducive to more precipitation in the Tianshan.

Figure 6 shows that water vapour flux into the Tianshan from the southwest prevails in winter (Figure 6b). The years of precipitation normalization greater than 1 in period 2 are chosen (1990, 1992, 1998, 2003, 2005, 2006, 2010) to represent periods of positive precipitation anomalies. Then we calculated the vertically integrated water vapour flux anomaly during these years. During years with positive precipitation anomalies, the total precipitable water vapour content (PWC) in most parts of Central Asia, including the Tianshan Mountains, is positive (Figure 6a). Central Asia is controlled by vigorous cyclones with one centre near the Caspian Sea and
another centre over the Arabian Peninsula. It can be deduced from Figure 6a that there are three water vapour paths into the Tianshan according to water vapour fluxes. The Tianshan is located on the southeast of a cyclone causing moisture flux from the European continent towards the Tianshan through the southern edge of the cyclone (water vapour path 1 in Figure 6a). Meanwhile, there exists a high PWC centre anomaly over the Arabian Sea. Due to the extension of the cyclone, abundant water vapour from the Arabian Sea is advected to the Tianshan Mountains (water vapour path 2 in Figure 6a). In addition, in the area of the Indian Ocean, a high-pressure system is located at low latitude that brings water vapour from the Bay of Bengal northward into the Tianshan Mountains (water vapour path 3 in Figure 6a).

### 3.2 Atmospheric circulation variability corresponding to anomalies of summer precipitation

The average summer (June, July, and August) precipitation in the entire Tianshan Mountains is 74 mm, accounting for 29.2% of the annual precipitation (Part I). Compared with winter precipitation, summer precipitation is more evenly distributed in the Tianshan with minimum precipitation in Western Tianshan (70 mm) and maximum in Northern Tianshan (87 mm).

Table 2 summarizes that the Tianshan summer precipitation is significantly negatively correlated with the SCAND index with a correlation coefficient of −0.45 and is statistically significant at the 95% confidence level (see also Figure 7b for time series). In terms of spatial distribution, the SCAND index is significantly negatively correlated with precipitation in Western Tianshan, Northern Tianshan, and Eastern Tianshan, but has only a weak relationship in Central Tianshan (Figure 7a). Additionally, PNA, PDO, and WP are also significantly correlated with Tianshan summer precipitation at the 95% confidence level (Table 2).

The regression pattern of the 500 hPa geopotential height anomaly with respect to the Tianshan summer precipitation anomaly during 1950–2016 presents an obvious SCAND pattern in its negative phase (Figure 8). It is characterized by negative height anomalies over Scandinavia as well as the Japan See and a positive
height anomaly over Siberia with its centre in the Ural Mountains. Apart from this, there is an obvious anomalous cyclone over Central Asia. This pattern exists from the lower to the upper tropospheres (not shown). The Tianshan Mountains lie in a zone of advection from the south between the anomalous cyclone and anticyclone. This structure further allows water vapour from the north to be transported towards the Tianshan Mountains in an anti-clockwise trajectory around the cyclone in the west of the study region. Together with water vapour transport from the South, this leads to increased summer precipitation.

Years with normalized summer precipitation greater than 1 (1954, 1958, 1969, 1972, 1981, 1987, 1992, 1993, 1998, 1999, 2003, 2005) and lower than −1 (1956, 1962, 1968, 1971, 1973, 1975, 1977, 1978, 1980, 1985, 1986, 2006, 2008) during 1950–2016 are selected to represent periods of increased precipitation and decreased precipitation, respectively. During years with positive precipitation anomalies, the geopotential height field exhibits the following characteristics: (a) the 500 hPa height anomaly

![Diagram](image)

**Figure 6** Water vapour flux (vectors; kg m\(^{-1}\) s\(^{-1}\)) and total precipitable water vapour content PWC (background contour; kg m\(^{-2}\)). (a) During years with positive precipitation anomalies; (b) on average in winter. Examples of typical water vapour path displayed as arrows for illustration only in panel (a): 1, from the European continent towards the Tianshan; 2, from the Arabian Sea into the Tianshan; 3, from the Bay of Bengal northward into the Tianshan. See the main text for interpretation of the water vapour paths. The area of the Tianshan Mountains is delineated with a green polygon

![Diagram](image)

**Figure 7** Correlation coefficient of SCAND index and the normalized Tianshan summer precipitation during 1950–2016, (a) spatial distribution, (b) time series. The area of the Tianshan Mountains is delineated with a green polygon

| Table 2 | The correlation coefficient between atmospheric indices and Tianshan summer precipitation during 1950–2016 |
|---------|---------------------------------------------------------------|
| NAO     | AO | PNA | PDO | AMO | EA | SCAND | WP |
| −0.13   | −0.01 | 0.30* | 0.29* | 0.03 | 0.26 | −0.45* | −0.31* |
| EP/NP   | ENSO | SOI | MEI | EATL/WRUS | ISM | DMI | WYM |
| 0.04 | 0.20 | −0.05 | −0.03 | 0.15 | −0.05 | −0.11 | −0.09 |

*Indicates significance at the 95% confidence level.
field presents a negative SCAND pattern which is a “Cyclone-Anticyclone-Cyclone” anomaly with a powerful anticyclone over the Ural Mountains (Figure 9a). (b) The Central Asian cyclone (60°E, 35°N) located over the eastern part of the Caspian Sea is profound (Figure 9a,b). Accordingly, a strong pressure gradient is formed between the Ural Mountains anticyclone in the north and the Central Asian cyclone in the south, which enhances airflow from high latitude regions to Central Asia. (c) The areas of the Iranian subtropical high (red line; 5,860 gpm) and the South Asian high (green line; 12,520 gpm) are relatively larger than those in years with below average precipitation. In contrast, the 500 hPa height anomaly field presents a positive SCAND

**FIGURE 8** Regression pattern of the 500 hPa geopotential height anomaly and 700 hPa horizontal wind anomaly onto the Tianshan summer precipitation anomaly for the period of 1950–2016. Geopotential height and horizontal wind have been standardized. Areas with net pattern and blue arrows indicate correlations that are significant at the 99% confidence level. The area of the Tianshan Mountains is delineated with a green polygon.

**FIGURE 9** 500 hPa geopotential height anomalies (gpm) and anomalies of horizontal wind speed (vector; m s⁻¹) in (a) years of above average precipitation (c) years of below average precipitation; (b) same as (a) and (d) same as (c) but for 200 hPa. Red delineates the location of subtropical High identified as above 5,860 gpm of the 500 hPa level. Green lines delineate the location of the South Asian High identified as above 12,520 gpm of the 200 hPa level. The area of the Tianshan Mountains is delineated with a green polygon.
pattern during periods of below average precipitation (Figure 9c,d). During these phases the Tianshan Mountains are controlled by anticyclonic tendencies.

In summer, water vapour arriving in Tianshan is mainly transported by the westerly wind (Figure 10b). During periods of increased precipitation, the PWC values in Siberia and most parts of Central Asia are positive (Figure 10a). The vertically integrated water vapour flux is similar to the abnormal characteristics of the 500 hPa horizontal wind field (Figure 10a). Water vapour from the Arctic Ocean is transported to Central Asia around the anticyclone located over Siberia and further transported to the Tianshan Mountains by the Central Asian cyclone just east of the Caspian Sea (blue dotted arrow; Figure 10). Consequently, the high pressure over Siberia and the low pressure over Central Asia play a crucial role in increasing the Tianshan summer precipitation. This finding is consistent with a study by Yang et al. (2011) who show that the Central Asian low-pressure system together with the Ural Mountain ridge triggers an atmospheric circulation that produces increased summer precipitation in Central Asia.

Summer precipitation in the Tianshan Mountains during 1950–2016 was decomposed into four oscillation periods of 2.9, 6.7, 12.2, and 33.5 years and one trend component (see Part I for details). The period of 33.5 years is treated as MDV in summer (Figure 11). Precipitation in the Tianshan showed an increasing trend, and summer precipitation entered a positive phase in 1985 (Figure 11). Furthermore, the MDV and trend added reveal that the Tianshan in summer was in a dry period before 1986 and then it entered a humid period.

According to the MDV, the summer precipitation in the Tianshan has decadal characteristics that can be separated into four distinct periods (Figure 11). To identify further patterns of atmospheric circulation affecting the precipitation during those four different periods, the regression patterns of the 500 hPa geopotential height anomaly to the Tianshan summer precipitation anomaly in these four periods are given by Figure 12. Periods 1 (1950–1963), 2 (1964–1984), 3 (1985–2004), and 4 (2005–2015) are defined. During period 1 and period 3 similar atmospheric circulation anomalies occurred in East Asia (Figure 12a,c. There is a significant “Anticyclone-Cyclone-Anticyclone” anomalous meridional wave pattern (“H”,“L” in Figure 12 represent high pressure and low pressure, respectively) in the coastal area of East Asia which is namely the East Asia-Pacific (EAP) teleconnection, also called the Pacific-Japan (PJ) teleconnection pattern (Huang and Li, 1987; Nitta, 1987). It contains a strong centre over the Japan Sea and two oppositely signed centres in the Okhotsk Sea, and the
South China Sea and the Philippines (Figure 12a,c). This teleconnection feature is more prominent in period 3 causing an anomalous easterly airflow extending from the Northwest Pacific inland into the mid-latitudes, even reaching Central Asia. The anomalous water vapour enters the Tianshan from its eastern boundary which contributes to the increase in summer precipitation. The regression pattern of the 500 hPa geopotential height anomaly with respect to the Tianshan summer precipitation anomaly in period 3 presents a SCAND pattern. The correlation coefficient between summer precipitation and the SCAND index in period 3 is $-0.55$ and is significant at the 99% confidence level indicating that both the SCAND and the EAP are affecting summer precipitation in period 3. On the other hand, there is no significant correlation with the SCAND pattern in period 1 (correlation coefficient between summer precipitation and the SCAND index is $-0.1$), suggesting that although SCAND has a strong impact on summer precipitation during the overall period 1950–2016, SCAND and the Tianshan summer precipitation were not correlated during 1950–1963.

According to the definition of EAP by Huang and Li (1987), IEAP is described as the linear combination of the standardized potential heights of the three areas A (125° E, 20° N), B (125° E, 40° N), and C (125° E, 60° N) (Figure 12a,c) according to

$$I_{EAP} = -\frac{1}{4} H_A' + \frac{1}{2} H_B' - \frac{1}{4} H_C'$$  (5)

**FIGURE 11** Characteristics of multi-decadal summer precipitation of the Tianshan based on EEMD method

**FIGURE 12** Regression pattern of the 500 hPa geopotential height anomaly and 700 hPa horizontal wind anomaly onto Tianshan summer precipitation anomalies for the periods of (a) 1950–1963, (b) 1964–1984, (c) 1985–2004, (d) 2005–2015. (The geopotential height and horizontal wind have been standardized). Shadow areas indicate that correlations are significant at the 99% confidence level. The symbol H denotes anticyclone and L denotes cyclone. A, B, C are three locations related to the definition of the EAP index $I_{EAP}$. See the main text for details. The area of the Tianshan Mountains is delineated with a green polygon.
where $H_A' = H_A \sin 45^\circ / \sin \beta_A$, $H_B' = H_B \sin 45^\circ / \sin \beta_B$, $H_C' = H_C \sin 45^\circ / \sin \beta_C$. $H_A$, $H_B$, and $H_C$ are the anomaly normalized geopotential heights of $A$, $B$, and $C$, respectively. $\beta_A$, $\beta_B$, and $\beta_C$ are the latitudes of $A$, $B$, and $C$, respectively.

There is a significant positive correlation between the $I_{EAP}$ and the summer precipitation in the Tianshan Mountains during period 1 ($r = 0.44$ at 95% confidence level) and period 3 ($r = 0.63$ at 99% confidence level) (Figure 13). In period 3, the years with $I_{EAP}$ greater than

**FIGURE 13** $I_{EAP}$ and the Tianshan summer precipitation anomaly during 1950–2016

**FIGURE 14** Water vapour flux (vectors; kg m$^{-1}$ s$^{-1}$) and total precipitable water vapour content PWC (background colour; kg m$^{-2}$) during years of positive summer precipitation anomalies (a) in period 1; (b) in period 3. Examples of typical water vapour paths are displayed as arrows for illustration only. See the main text for interpretation of the water vapour paths. The area of the Tianshan Mountains is delineated with a green polygon.
1 (1986, 1987, 1991, 1992, 1993, 1998) have been chosen to represent periods of a positive EAP phase. During years with EAP positive phase anomalies, a significant “Anticyclone-Cyclone-Anticyclone” anomalous meridional moisture pattern in the coastal area of East Asia (Figure S1) is present, bringing water vapour from the Northwest Pacific into Central Asia and the Tianshan Mountains. However, the relationships between $I_{\text{EAP}}$ and summer precipitation in periods 2 and 4 are weak. EAP is an important atmospheric circulation factor affecting the Tianshan summer precipitation but only during the periods of 1950–1963 and 1985–2004.

Years with above average normalized summer precipitation in period 1 (1954, 1958) and period 3 (1981, 1987, 1992, 1993, 1998, 1999, 2003) were selected to represent summers with enhanced summer precipitation in these periods. The mean vertically integrated water vapour fluxes anomaly during these summers is shown in (Figure 14). During summers with above average precipitation in periods 1 and 3, there are westward water vapour fluxes from East Asia to Central Asia entering the Tianshan Mountains from both its eastern boundary and its western boundary alongside the anticyclone on the Western Tianshan (Figure 14). Meanwhile, over the Ural Mountains an anticyclone exists in both periods. However, in period 1, the influence of this anticyclone does not suffice to promote water vapour flux from the Arctic Ocean into the Tianshan Mountains. This once again indicates that the SCAND pattern had little effect on summer precipitation during period 1. In period 3, the obvious water vapour transport path from high latitudes reaches Tianshan due to the stronger anticyclone over the Ural Mountains. Consequently, the increase in the Tianshan summer precipitation in period 3 is jointly promoted by SCAND and EAP. As shown in Figure 15, the regression patterns of the 200 hPa geopotential height anomaly concerning the Tianshan summer precipitation anomaly in period 2 (1985–2004) presents a significant “Anticyclone-Cyclone-Anticyclone-Cyclone” anomalous meridional wave pattern in Euroasia which is similar to the negative phase of the circum-global teleconnection (CGT) pattern, also called the Silk Road pattern (SRP).
The SRP pattern is not found to be significantly correlated with summer precipitation in the Tianshan Mountains in the geopotential height field of periods 1, 3, and 4. By calculating the correlation coefficient between the SRP index and the Tianshan summer precipitation, it was found that the two are only significantly correlated in period 2 (Figure 16) indicating that SRP was an important circulation factor affecting the Tianshan summer precipitation only during the period of 1964–1984. Previous studies found that SRP is closely related to the strength of the Asian jet in summer (Chen and Huang, 2012) and that an enhanced Asian jet favours the propagation of stationary Rossby waves causing increased precipitation from the “westerlies-dominated climatic regime” (Huang et al., 2015). From 1964 to 1985, the SRP has been in a prolonged negative phase (Figure 16) resulting in a period of less precipitation in the Tianshan Mountains during this period.

4 | DISCUSSION

The long-term trend of winter precipitation in the Tianshan Mountains exhibits non-linear characteristics, first increasing and then beginning to decrease after 1979. However, according to Part I, winter precipitation showed a clear upward non-linear trend in the Eastern, Northern, and Central Tianshan Mountains. It showed a downward non-linear trend only in the Western Tianshan Mountains. Therefore, since the winter precipitation is mainly distributed in Western Tianshan, the decline of Tianshan precipitation in winter is mainly due to the decline in precipitation in the Western Tianshan Mountains. For summer precipitation, if only the linear trend of traditional statistical methods is used for analysis, it can only be found that the summer precipitation in the Tianshan Mountains has a positive linear trend (Figure 17). When calculating the accumulative anomaly, the Tianshan in summer entered a period of excessive precipitation after 1986 when the accumulative anomaly reached its minimum in the overall time series (Figure 17). However, it is difficult to identify characteristics of multi-decadal variation in precipitation. In this study, we used the EEMD method to reveal the existence of multi-decadal scale variability which can be further used to analyse the influence of different atmospheric circulation patterns in different periods, thereby deepening the understanding of the reasons for precipitation changes in the Tianshan Mountains.

Atmospheric circulation of low and high latitudes influences the climate of the Tianshan Mountains which are located in the mid-latitudes. According to our results, the position and intensity of Eurasian teleconnections and East Asian teleconnections in the middle and high latitudes have had an impact on Tianshan precipitation during different periods. Also, the Indian high-pressure system at low latitude contributed to the variability of Tianshan winter precipitation. In addition, we found that the areas of the Iranian subtropical high and the South Asian high in the years with above average precipitation were relatively larger than those in years with below average precipitation (Figure 9), which may be related to the low-latitude Indian monsoon and Indian precipitation. The subtropical high, the South Asian high and the monsoon rain belt are in a relationship of interaction and teleconnectivity (Yu and Wang, 1989; Zhang et al., 1995; Zhang and Zhi, 2010). Previous studies have examined that the moisture transfer process enhances subtropical highs significantly as well as the meridional development of flow (Li and Luo, 1988; Matsumura et al., 2015). In fact, condensation heating in the eastern part of China, which is caused by the influx of the southwest monsoon airflow, is the most direct driving force for the strengthening of the western Pacific subtropical high (Qian and Yu, 1991). Besides, the latent heat release from precipitation over India is conducive to the strengthening of the South Asian high as a warm high-pressure system (Qian et al., 2002a, 2002b; Liu et al., 1999). However, the ISM, DMI, and WYM indices and Tianshan precipitation in winter and summer all show weak correlations according to our results. There may be a lead–lag relationship between Indian summer monsoon precipitation and Tianshan precipitation which we have not investigated in this study. The more detailed investigation of the association of Indian summer monsoon with Tianshan
precipitation is worthy of further study. As an important feature of tropical circulation, the role of ENSO cannot be ignored. Although according to our calculations, the correlations between winter and summer precipitations in the Tianshan Mountains and ENSO failed the significance test (Tables 1 and 2), the correlation coefficients between ENSO and Tianshan inter-annual precipitation, spring (March, April, May) precipitation, and autumn (September, October, November) precipitation reach 0.44, 0.37, and 0.43 at 95% confidence level, respectively. This indicates that ENSO has a profound impact on precipitation in the Tianshan Mountains. Previous research indeed verified that ENSO has a significant positive correlation with the annual precipitation in Central Asia and may be caused by inter-annual variation of ENSO (McPhaden et al., 2006; Hu et al., 2017). Besides, our research shows (Table 2) that there is also a significant correlation between Tianshan summer precipitation and PDO which is described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al., 1997). However, the precipitation in the four sub-regions of Tianshan show different changes and differ between seasons. The relationships between ISM, ENSO, PDO and precipitation, as well as water vapour transport in sub-Tianshan regions, and how ISM, ENSO, and PDO affect them will be the focus of future work.

5 | CONCLUSION

In this study, the multi-decadal variability of winter and summer precipitation over the Tianshan Mountains during 1950–2016 are analysed based on the EEMD method. Furthermore, the relationships between atmospheric indices and Tianshan precipitation are revealed. The winter precipitation has a long-term trend first increasing and then decreasing after 1979. However, the intensity of the multi-decadal variability of precipitation is greater than the long-term trend of precipitation. Therefore, the result of the combined effect of the two is that the Tianshan Mountains in winter entered a humid period in the 1980s.

A significantly positive correlation between ETAL/WRUS and winter precipitation is revealed. The EATL/WRUS multi-decadal variation is very similar to that for winter precipitation in the Tianshan. After 1988, the enhanced meridional feature of the EATL/WRUS pattern causes water vapour from low-latitude ocean areas to enter the Tianshan Mountains between the low pressure over the north of the Caspian Sea and the positive pressure over Northern India, resulting in a wet period in the Tianshan in winter.

The summer precipitation in the Tianshan Mountains has an obvious multi-decadal scale of 33.5 years and shows a non-linear increasing trend causing the Tianshan Mountains to enter a humid period after 1986 in summer. The SCAND is an important circulation pattern affecting Tianshan summer precipitation. During the negative phase of SCAND, the low pressure over Central Asia and the high pressure over the Ural Mountains together drive water vapour from the Arctic Ocean towards the Tianshan Mountains. In addition, during 1985–2004, Tianshan summer precipitation was also affected by the EAP pattern. An enhanced flux of water vapour in this period occurred eastward from East Asia to the Tianshan Mountains. Furthermore, the SRP pattern had a significant impact on Tianshan summer precipitation during 1964–1984. SRP was in a negative phase during that period which drove the Tianshan Mountains into below average precipitation during this period.

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AUTHOR CONTRIBUTIONS

Xuefeng Guan: Conceptualization; formal analysis; investigation; methodology; resources; visualization; writing-original draft. Junqiang Yao: Data curation; software. Christoph Schneider: Supervision; validation; writing-review & editing.

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