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Interannual precipitation variations in the mid-latitude Asia and their association with large-scale atmospheric circulation

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This study analyzed the spatial differences of the precipitation variations in the mid-latitude Asia and their possible physical mechanisms during 1960–2009. The annual precipitation showed an opposite variations between the westerlies-dominated arid Central Asia (ACA) and monsoon-dominated North China (NC) during the study period. Given the different contributions of seasonal precipitation to annual total precipitation in ACA and NC, the atmospheric circulation anomalies during the major precipitation seasons (winter in ACA/summer in NC) were analyzed. In winter, negative North Atlantic Oscillation may cause negative height anomalies over the north side and positive anomalies over the south side of the ACA. Together, the enhanced pressure gradient and anomalous westerly wind brings more water vapor to ACA, and leaves less precipitation in NC. In summer, the low-pressure anomalies in Northeast China, along with a weaker summer monsoon and negative height anomalies in Eastern Europe together contribute to reduced (excessive) summer precipitation in NC (ACA). The interactions between ENSO and NAO may result in the opposite precipitation variations between ACA and NC. A significant 2–3-year cycle is identified in ACA, which is linked to the variations of westerly circulation in the middle troposphere.

mid-latitude Asia, interannual precipitation variations, westerlies-dominated climate regime, regional westerly indexes, Troposphere Biennial Oscillation (TBO)

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The mid-latitude Asia continent can be roughly divided into two distinct climatic regions: the monsoon dominated eastern-southern parts of Asia and the mid-latitude westerlies dominated arid Central Asia (ACA) [1]. The ACA, one of the largest arid regions in the middle latitudes, contains the arid areas of Central Asia, arid northwestern China and the arid Mongolian Plateau. Due to influence of westerly circulation, the annual precipitation across the ACA falls mainly in winter and spring [2,3]. The eastern part of the mid-latitude Asia (e.g. the Northern China) located in the border region of the East Asian Summer Monsoon, with annual precipitation mainly fall in summer. Our previous studies showed that the humidity (precipitation) variations in ACA are opposite to those of summer monsoon dominated East China during the Holocene and over the last 1000 years [4–7], suggesting that there is a westerlies-dominated climate regime in the mid-latitude Asia [1]. This "westerlies-dominated climate regime" describes the opposite precipitation/humidity changes between ACA and the summer monsoon dominated regions [1]. The "westerlies-dominated climate regime" seems also exist on interannual and decadal scales. For example, Chen et al. [8] showed that the annual precipitation in central Asia has been significantly increased over the past 80 years. In the arid northwestern China, the precipitation and soil moisture has increased since the 1950s [9–11]. As a result, the climate in this region has changed from a warm-dry to warm-wet regime since the middle 1980s [12]. The monsoon dominated North China (NC) and

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*Corresponding author (email: fhchen@lzu.edu.cn) the east part of the northwestern China, however, are becoming warmer and drier over the past 50 years [9,13,14]. The tree-ring reconstructed drought index in arid northwestern China and in the Asian summer monsoon boundary also supports the observed opposite humidity changes between the arid and monsoon regions in the past 50 years [15,16].

Prior studies have examined the variations of precipitation on decadal and interannual time scales in the monsoon dominated East Asia. For example, the East Asian summer monsoon has gradually weakened over the past 100 years [17–19] and the humidity in the Asian summer monsoon boundary is decreasing [16]. An important factor that influences the NC precipitation is the El Niño Southern Oscillation (ENSO). Warmer (cooler) eastern tropical Pacific Ocean can cause a drier (wetter) condition in NC [20,21]. Feng and Hu [22] found that the ENSO can first influence the Indian monsoons through the Walker Circulation and then influences the interannual variation of precipitation in NC. Lu [23] showed that the air-sea interaction in the eastern tropical Pacific Ocean influences the location of the upper-level westerly jet stream over East Asia, and in turn influence the moisture transport to the NC and the summer rainfall variations. The studies on the precipitation changes in the ACA, however, are relatively limited. The study by Su and Wang [10] showed that the increasing humidity in northwestern China in the 1980s was concurred with the shift of ENSO from a cold to a warm phase at the same time. Another factor influences the precipitation in ACA is the North Atlantic Oscillation (NAO). Weaker (stronger) NAO is associated with more (less) precipitation in ACA [3]. NAO and ENSO are significant coherence at 2–4-year time scale [24] and effect on the regional circulation and Climate in ACA [25].

As the temperature increase may differ in different regions during the 20th century, and it leads to increased evapotranspiration over land and to affect the global water cycle [26]. However, previous studies on precipitation changes in the mid-latitude Asia have mainly focused on changes in the specific regions (e.g. Northern China, or ACA). No previous studies have analyzed the precipitation changes over the entire Mid-latitude Asia. This study evaluated the interannual precipitation variations in the mid-latitude Asia and their regional differences during 1960–2009. Specifically, are there significant regional differences in interannual precipitation variations between the westerlies-dominated region and the monsoon-dominated region in mid-latitude Asia? What are the physical mechanisms that influence the interannuual precipitation variations in those regions? Answering those questions is important because the anomalistic fluctuation of precipitation can significantly impact the water supply for both natural and managed ecosystem in the arid and semiarid region. This study also helps provide a foundation for understanding the mechanisms of the westerlies-dominated climate regime in the mid-latitude Asia on centennial and millennium time scales [4–7].

1 Data and methods

This study focused on mid-latitude Asia (35°–53°N, 50°–120°E, Figure 1). In our evaluation of the inerannual precipitation changes, we used the gridded monthly precipitation from 1901 to 2009 developed at the Climate Research Unit, University of East Anglia (http://www.cru.uea.ac.uk). This dataset covers the global land areas at 0.5°×0.5° spatial resolution. Compared to other existing observational-based precipitation datasets, this dataset has higher spatial resolution and extends over a longer period. Before using the CRU data, we evaluated the quality of the data by checking the available observations that were used to construct the gridded data. Our examination showed there were very few observations available in northwestern China before the 1960s. Therefore, this study only used data from 1960 to 2009.

In addition to the precipitation data, the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data [27] were used to examine the atmospheric circulation and moisture flux associated with the interannual precipitation variations in the mid-latitude Asia. The moisture flux was integrated from 1000 to 300 hPa. The monthly mean zonal and meridional wind (u, v) in the pressure coordinates are used to analyze variations in the mid-latitude westerly jet stream in the study region. To examine the impact of large-scale climate forcings on the interannual precipitation, the regional westerly index [28] and the multivariate ENSO index (http://www.esrl.noaa.gov/psd/enso/mei/) and their relationships with precipitation over our study regions were also analyzed Additionally, the empirical orthogonal function (EOF) [29] and the Multi-Taper spectral analysis Methods (MTM) [30] were used to investigate the primary spatial variability and dominant cycles in the precipitation.

2 Results

2.1 Spatial differences of precipitation variations

The annual precipitations in the past 50 years over the entire domain were used for the EOF analysis. The first two EOF modes explained 15.4% and 10.3% of the total variance, respectively. The first EOF (Figure 2(a), hereafter EOF1) shows a clear dipole mode between the west and east parts of the domain. The EOF2 (Figure 2(b)) shows the opposite

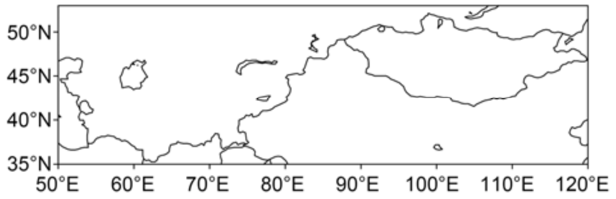

Figure 1 The mid-latitude Asia.

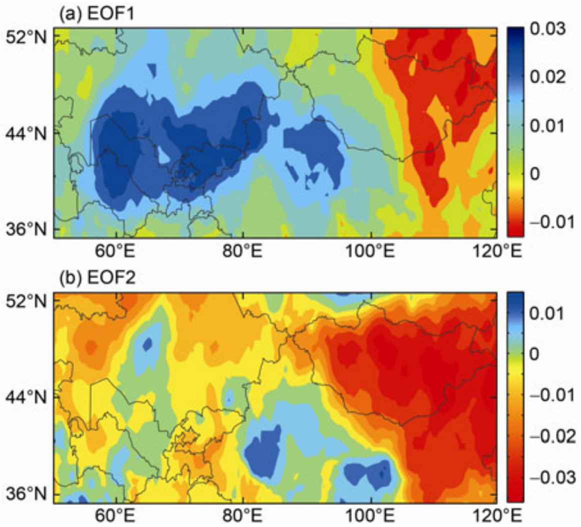

Figure 2 The first two EOFs modes computed based on annual total precipitation.

precipitation variations between northwestern China and NC. Therefore the first two components both confirmed that there was also a "westerlies-dominated climate regime" in mid-latitude Asia during the past 50 years.

The temporal variations of the first two principal components (termed PC1 and PC2) associated with the first two EOF modes are shown in Figure 3. Both the PC1 and PC2 have been increasing in recent 50 years. Superimposed on the liner increasing trend are interannual and decadal variations. Combined with the EOF1 and EOF2, the above facts suggest ACA's annual precipitation is increasing, but decreasing in NC over the past 50 years. These results are also consistent with the previous findings that the Xinjiang region is becoming wetter in recent decades [12,31]. There is a significant (at 95% confidence level) 2–3-year cycle in PC1 by MTM. The PC2, however, contains a significant 25-year cycle and a slightly weaker 2–3-year cycle (not shown). Additionally, the PC2 shows a noticeable increasing trend since the late 1980s, suggesting that the precipitation is increasing in northwestern China but decreasing in NC over the past nearly 20 years.

2.2 Atmospheric circulation and water vapor anomalies

The results in the previous sections suggested obviously opposite variations between the westerlies dominated ACA and the monsoon dominated NC. To better understand the atmospheric circulation associated with the interannual precipitation variations, a 9-year high-pass filter was applied to the PC1. This filter will keep variations shorter than 10 years in the filtered data series. We then selected five high score years (1969, 1987, 1993, 2002 and 2003) and five low score years (1974, 1975, 1995, 2000 and 2008) of the PC1 on interannual variations. As shown in Figure 3, high scores indicate wetter condition in ACA and drier condition in NC, and *vice versa*.

The atmospheric circulations and moisture flux during the high and low scores years are compared and contrasted. The composite of 850, 500 and 200 hPa geopotential height during the high and low score years showed robust barotropical structures (not shown), so in the following we only focused on the geopotential height at 500 hPa. Because the annual precipitation mainly falls during winter and spring in ACA, the atmospheric circulation anomalies in winter (Figure 4(a)) may largely represent the circulation anomalies associated with the wetter years in ACA. Figure 4(a) suggests that during the wetter years in ACA, there are negative height anomalies in the mid-latitude (30°–50°N) North Atlantic and tilt northeast to cover the entire Siberia. In the Asian continent, significant negative anomalies appeared in regions north of ACA and the Siberia. Associated with the negative height anomalies are the positive anomalies in high-latitude North Atlantic (near Iceland) and a positive belt extends from tropical Atlantic and North Africa to East Asia. Significant positive anomalies appeared in the high-latitude North Atlantic, North Africa and the regions south of ACA and the southern Tibetan Plateau. The positive height anomalies in the high-latitude Atlantic and negative height anomalies in the mid-latitude Atlantic suggest a weaker NAO during the wetter years in ACA. These results are consistent with previous finding that the NAO can significantly influence the winter precipitation in Central Asia [3,34]. Associated with the negative height anomalies from

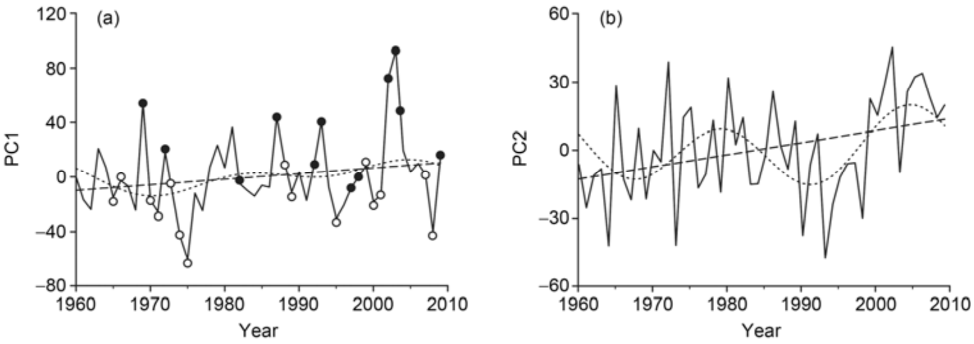

Figure 3 Time series of the principal components associated with the first two EOFs ((a), (b)). The dashed lines indicate the overall linear trend and dotted lines indicate the 9-years running mean. The filled (open) circles in (a) indicate El-Niño (La-Niña) years [32,33], respectively.

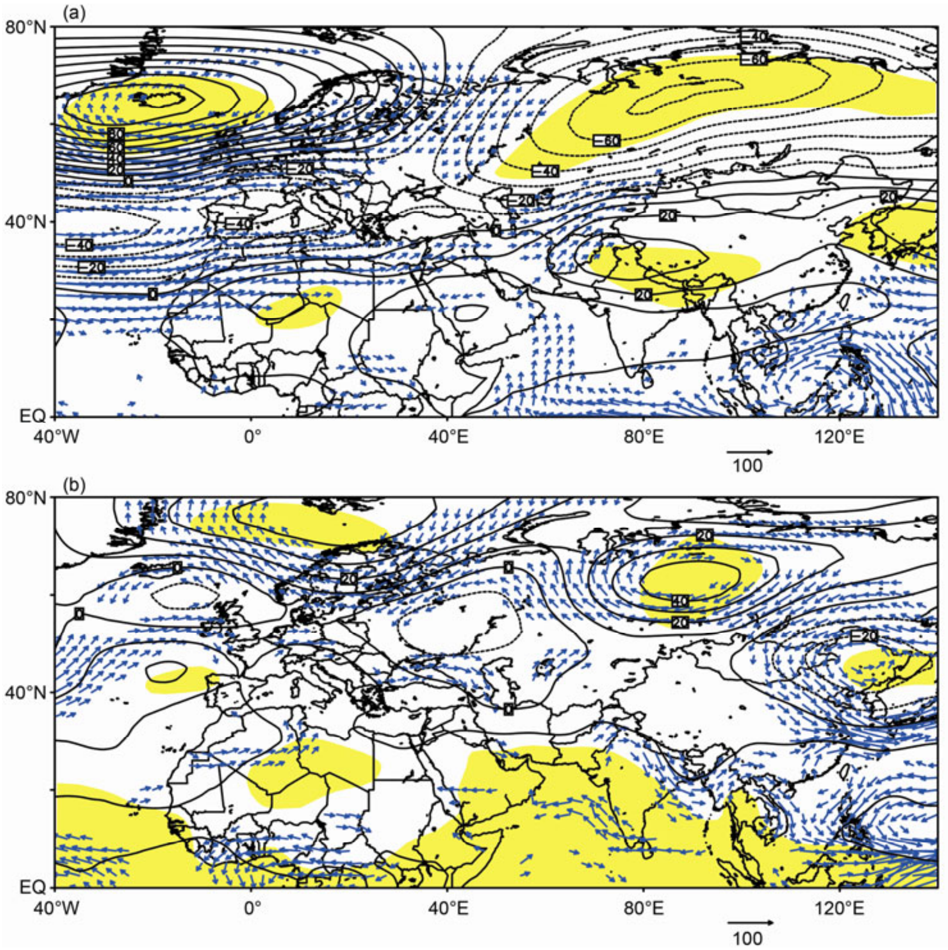

Figure 4 Differences of winter (a) and summer (b) 500 hPa geopotential heights (unit is gpm) and the vertically integrated water vapor flux (kg m^{-1} s^{-1}) between the high and low PC1 scores years. Shadings indicate the anomalous heights are significant at 95% confidence level.

mid-latitude Atlantic to Siberia and the positive anomalies in the south are anomalous moisture flux from Mediterrerrean to the ACA. The significant positive height anomalies near the southern Tibetan Plateau also encourage anomalous moisture flux from the Arab Sea to the ACA. The two anomalous moisture fluxes converge in the ACA and bring more precipitation there. During the same period, associated with the negative height anomalies in Siberia, anomalous moisture flux diverges from Siberia to the NC and causes less precipitation there. The reverse is true during the drier years in ACA.

Because the annual precipitation in NC mainly falls in summer and there are opposite precipitation variations between NC and the ACA (Figure 2(a)), the summer atmospheric circulation anomalies during the high PC1 score years (Figure 4(b)) may largely represent the circulation anomalies associated with drier conditions in NC. During the summer time of the high PC1 score years, there are negative height anomalies in Northeast China. Associated with this negative height anomalies are anomalous moisture flux from the dry Mongolia to NC. Additionally, the positive height anomalies appear in South China, the South China Sea and the western tropical Pacific, suggesting that the western Pacific subtropical high is displaced southward and westward than the normal. As a result, the upper-level westerly jet stream will displace southward and provide fewer disturbances in NC and hamper the precipitation development [23]. The anomalous moisture transport from the dry Mongolia to NC help create moisture divergence. The moisture divergence, the southward displacement of subtropical high and fewer disturbances in NC all together result in less precipitation in NC during the high PC1 score years. On the other hand, a small amount of water vapor coming from upwind lakes is transported to ACA due to the weaker negative height anomalies over the north of Caspian Sea. The reverse is true during the low PC1 score years.

3 Discussion

Our results suggested obviously opposite interannual precipitation variations between the westerlies dominated ACA and the monsoon dominated NC during the past 50 years (Figures 2 and 3), confirmed that the "westerlies-dominated climate regime" that operated during the Holocene [1,4,5] also existed on interannual variations.

The NAO may influence the precipitation in the ACA [3] (Figure 4(a)). The NAO is a dominant mode of winter climate variability in the North Atlantic region, ranging from central North America to Europe and far into northern Asia, and even covering the whole Northern Hemisphere [35,36]. Figure 4(a) shows that negative NAO phase in winter is associated with excess precipitation in ACA, which is consistent with previous studies [3]. The annual precipitation in the major arid area of the ACA falls mainly in winter and spring. Recent study showed that the increasing annual total precipitation in recent 30 years is mainly caused by the increment of winter precipitation [8]. Therefore, the weakening winter NAO in recent decades likely played an important role in causing the increasing precipitation in ACA in recent 30 years.

Figure 4(a) shows the excess moisture transport from the Mediterranean and the Caspian Sea to the ACA during the high PC1 score years (wetter conditions in ACA), therefore, the changes of evaporation in upwind lakes (e.g. the Caspian Sea and the Aral Sea) and the shrinking of those large lakes may also influence the water cycle and precipitation in ACA. A modeling study by Jin et al. [37] showed that the drought in ACA in early Holocene was caused by northward displacement of the westerly jet and reduced evaporation in upwind inland lakes (e.g. the Caspian Sea) and the North Atlantic Ocean, suggesting the evaporation in the upwind lakes may also influence the precipitation changes on centennial and millennium scales. Therefore, the strength of the westerly and the associated changes of water vapor at the middle latitudes are also important factors that influence the precipitation variations in ACA. To further examine the relationship between westerly circulation and the precipitation in ACA, the annual and winter regional westerly indexes are computed following the method described by Li et al. [28]. In particular, the difference of 500 hPa geopotential height between 35° and 55°N are calculated and then averaged over 50°W–50°E to represent the strength of the upstream westerly wind. Figure 5(a) shows the temporal variations of the winter westerly index and the winter precipitation in ACA during the past 50 years. It shows an in-phase relationship of the two time series over the study period, albeit a few exceptions. The correlation between the two time series is as high as 0.51, which is significant at 99% confidence level. These features in the variations support a strong linear relationship between the upper stream westerly wind and the precipitation in ACA.

In addition to the impacts of NAO and westerlies, the precipitation variations in the mid-latitude Asia are also related to the variations of El Niño-Southern Oscillation (ENSO) [20,21,22,38]. As shown in Figure 5(b), the variations of summer precipitation in NC (35°–42°N and 110°–120°E) show an out-of-phase relationship with the multivariate ENSO Index. The correlation between the two time series is −0.46, which is significant at 99% confidence level. These fairly consistent out-of-phase variations suggested that alternations of ENSO played an important role in causing the variations of the summer precipitation in NC. Figure 3(a) also shows that the high PC1 scores years (wetter conditions in ACA and drier condition in NC) concurred to the El Niño years, and low PC1 scores years (drier condition in ACA and wetter condition in NC) were in line with the La Niña years. These results indicate that the ENSO may also

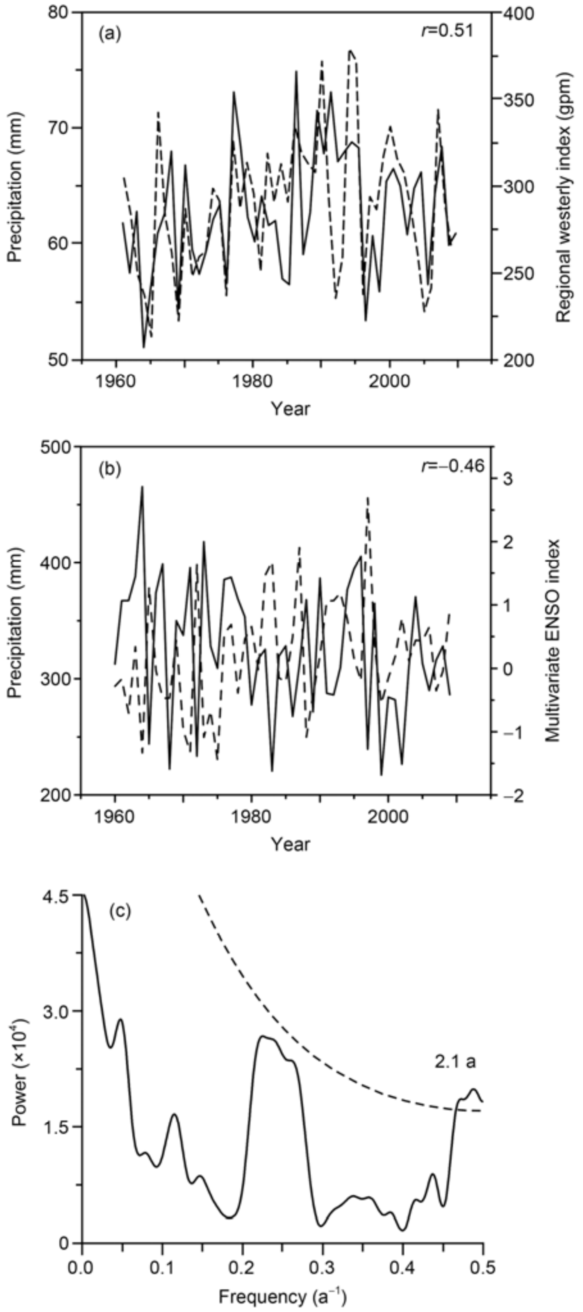

Figure 5 (a) Time series of the winter regional westerly index (dotted line) and the winter precipitation in ACA (solid line); (b) time series of the multivariate ENSO index (dotted line) and the summer precipitation in NC (solid line); (c) the MTM power spectrum of the annual regional westerly index.

play some roles in causing the opposite precipitation variations between the ACA and NC. However, how the ENSO and NAO interact the relative roles of the two factors on the precipitation variations in the mid-latitude Asia and the seasonality of their effects is still not clear, and certainly deserves further investigation.

There is a significant 2–3-year cycle in the annual precipitation in the mid-latitude Asia. This cycle may be related to the Quasi Biennial Oscillation in the stratosphere or the Troposphere Biennial Oscillation (TBO) [39,40]. Previous study suggested that strong winter Asian monsoon may strengthen the summer monsoon in the following summer, which results in weak winter Asian monsoon next year. Li et al. [41] argued that these mechanisms may well explain the TBO in East Asia. However, these mechanisms cannot explain the 2–3-year cycle in precipitation variations in ACA. Chen et al. [8] argued that the TBO signal of westerly circulation is the decisive factor associated with precipitation in ACA. The MTM method showed that the westerly wind over 50°W–50°E contains significant (at a 99% confidence level) TBO signal during the past 50 years (Figure 5(c)). Because the upper stream westerly wind played an important role in the variations of precipitation in ACA (Figure 5(a)) by influencing the water transport to the regions, the TBO signal in precipitation in ACA is likely related to the variations of the westerly wind. Therefore, the physical mechanisms that caused the TBO variations are different between westerlies dominated regions and monsoon dominated regions.

4 Conclusions

This study analyzed the interannual precipitation variations over the mid-latitude Asia and their regional differences during the past 50 years. Our results showed opposite precipitation variations between the westerlies dominated ACA and monsoon dominated NC on decadal and interannual time scales. In winter, the excess precipitation in ACA is associated with weaker NAO. The negative 500 hPa geopotential height anomalies from mid-latitude North Atlantic to the Siberia and the positive height anomalies on the south lead to stronger westerlies and more water vapor transported from the Meditererrean and Caspian Sea to the ACA and cause the excess precipitation there. In summer time, the negative height anomalies in Northeast China and the southward displacement of the western Pacific subtropical high hamper the moisture transport from the Ocean to NC and caused a drier condition in the region.

The winter precipitation in ACA is also closely related to the strength of the westerly circulation in the mid-latitude. The enhancing regional westerly wind from the North Atlantic to Central Asia is one of the important factors influencing the precipitation variations in ACA during the past 50 years. The strong 2–3-year cycle in ACA is also related to the TBO of the westerly circulation.

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