Central Asian Precipitation Shaped by the Tropical Pacific Decadal Variability and the Atlantic Multidecadal Variability

JIE JIANG,^{a,b} TIANJUN ZHOU,^{a,b,c} XIAOLONG CHEN,^a AND BO WU^a

^a State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

^b University of the Chinese Academy of Sciences, Beijing, China

^c CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing, China

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ABSTRACT: Known as one of the largest semiarid to arid regions in the world, central Asia and its economy and ecosystem are highly sensitivity to the changes in precipitation. The observed precipitation and related hydrographic characteristics have exhibited robust decadal variations in the past decades, but the reason remains unknown. Using the pacemaker experiments of the Community Earth System Model (CESM1.2), we find that the tropical Pacific decadal variability (TPDV) and the Atlantic multidecadal variability (AMV) are the main drivers of the interdecadal variations in central Asian precipitation during 1955–2004. Both the decadal-scale warming of the tropical Pacific and North Atlantic are favorable for wetter conditions over central Asia. The positive TPDV is accompanied with high sea level pressure (SLP) over the Indo–western Pacific warm pool. Southwesterly winds along the northwestern flank of the high SLP can transport more moisture to southeastern central Asia. The warm AMV can excite a circumglobal teleconnection (CGT) pattern. A trough node of the CGT to the west of central Asia drives an anomalous ascending motion and increased precipitation over this region. The results based on the CESM model are further demonstrated by the pacemaker experiments of MRI-ESM2-0. Based on the observational TPDV and AMV indices, we reasonably reconstruct the historical precipitation over central Asia. Our results provide hints for the decadal prediction of precipitation over central Asia.

KEYWORDS: Precipitation; Air–sea interaction; Interdecadal variability

1. Introduction

Central Asia, which includes Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan, is a semiarid to arid region located in the midlatitude of Eurasia. Large variations in water cycle and the significant warming trend make central Asia one of the “hotspots” of climate change (Giorgi 2006; Chen et al. 2009). Water shortage has been a serious problem for central Asia, and a significant shrinking of lake area, reduction of snow cover, decline of water levels, and decrease in soil moisture have been observed over this region in recent decades (Micklin 2007, 2016; Unger-Shayesteh et al. 2013; Mueller and Zhang 2016). Understanding the reasons for historical changes in central Asian precipitation is a prerequisite of climate change adaptation and mitigation activities.

While the physical processes that affect the interannual variations of central Asian precipitation have been well documented, including the role of the subtropical westerly jet (SWJ), El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the east Atlantic–western Russia pattern

(EA/WR), and the polar–Eurasian pattern (PE) (Syed et al. 2006; Mariotti 2007; Barlow and Tippett 2008; Bothe et al. 2012; Filippi et al. 2014; Yin et al. 2014; Zhao et al. 2014; Gerlitz et al. 2018). The effort devoted to the long-term and decadal variations of central Asian precipitation is quite limited due to the lack of reliable long-term observational precipitation records (Unger-Shayesteh et al. 2013).

Previous work has found that the interdecadal and multidecadal variability in the Pacific and Atlantic can effectively affect regional and even global climate, including southwest Asia, East Asia, and South Asia, the neighboring regions of central Asia (e.g., Hoell et al. 2015, 2017a,b; Krishnamurthy and Krishnamurthy 2016, 2017; Yang et al. 2017). For instance, the winter precipitation over southwestern Asia increases following the positive phase of Pacific decadal variability (PDV; Hoell et al. 2015, 2017a,b). The abrupt shift in the Pacific sea surface temperature (SST) and associated atmospheric circulation contribute to the recurrent drought events in central-southwest Asia in spring since 1999 (Lyon et al. 2014). The meridional shift of rainfall band over East Asia at interdecadal time scale is related with the interdecadal variability in both the Pacific and Atlantic (Qian and Zhou 2014; Si and Ding 2016; Yang et al. 2017). The interdecadal variability of Indian monsoon rainfall is modulated by the decadal component of the Pacific decadal oscillation (PDO), the Atlantic multidecadal oscillation (AMO), and the Atlantic tripolar SST anomaly (SSTA) mode (Krishnamurthy and Krishnamurthy 2016, 2017). In addition, the opposite signals of summer precipitation between central Asia and midlatitude East Asia on decadal scales are dominated by the AMO (Huang et al. 2015).

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Corresponding author: Tianjun Zhou, zhoutj@lasg.iap.ac.cn

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The AMO can influence the interdecadal variations of Eurasian climate through a circumglobal stationary baroclinic wave train (Si and Ding 2016). As for central Asia, output from atmospheric general circulation models (AGCMs) forced by idealized SST anomalies shows that the decadal variations of central Asian precipitation may be forced by Pacific decadal SST variability (Hoell et al. 2015). However, this relationship is insignificant in both observations and AGCM simulations forced by observed global SSTs (Lyon et al. 2014; Hoell et al. 2017a). Analysis of observational data found that there is no significant correlation between central Asian precipitation and common climatic indices at the interdecadal time scale (Hu et al. 2017). There has been no satisfactory explanation for the paradox up to now. Is central Asia in the “blind spot” for the interdecadal or multidecadal variability in the Pacific and Atlantic, or does the low correlation come from the competition between different oceanic forcings? This remains an open question waiting for investigation.

Precipitation records are more reliable after the 1950s over central Asia (Fig. 1). The different phase combinations of the interdecadal variability in the Pacific and Atlantic may obscure the SST-related signals in observation during the short period. The impacts of SST over single ocean basins on global or regional climate anomalies are investigated by using either AGCMs or ocean–atmosphere coupled general circulation models (CGCMs) (e.g., Schubert et al. 2009; Kosaka and Xie 2013). The U.S. Climate Variability and Predictability Research (CLIVAR) Drought Working Group designed a series of idealized AGCM experiments to reveal the influence of Pacific and Atlantic SST variability (Schubert et al. 2009). Such kinds of experiments forced by prescribed SST patterns have been used to understand the interdecadal variations in precipitation over Asia (Hoell et al. 2015; Yang et al. 2017; 2019), North America (Pegion and Kumar 2010; Yang et al. 2019), and the global monsoon domain (Jiang and Zhou 2019).

Recently, pacemaker-like numerical experiments that restore the historical observational SST anomalies in specific basins based on CGCMs are an emerging useful method to understand the remote impact of SST anomalies over the Pacific or Atlantic (e.g., Kosaka and Xie 2013; Kamae et al. 2017; Huang et al. 2019). Such kinds of pacemaker experiments have been used in the design of the phase 6 of the Coupled Model Intercomparison Project (CMIP6) such as the Global Monsoon Model Intercomparison Project (GMMIP; Zhou et al. 2016) and the Decadal Climate Prediction Project (DCPP; Boer et al. 2016). Based on well-designed pacemaker experiments of fully coupled models driven by the observational SST over Pacific or Atlantic, we aim to understand the interdecadal variations in central Asian precipitation. As previous studies emphasized the tropical processes related to the interdecadal variability in the Pacific and the influence of SST variability over North Atlantic in modulating precipitation over the neighboring regions of central Asia (e.g., Hoell et al. 2015, 2017a,b; Huang et al. 2015), we focus on the impact of tropical Pacific decadal variability (TPDV) and Atlantic multidecadal variability (AMV) on central Asian precipitation in this study. In particular, we hope to answer the following

FIG. 1. (a) Total count of monthly station observations contributing to each grid cell over central Asia during 1891–2016 in the GPCC precipitation dataset. The average of monthly station observations contributing to each grid cell during (b) 1920–54 and (c) 1955–2004. The contours in (b) and (c) denote the geopotential height (GH = 0.5, 1.0, 2.5, 4.0 km).

questions: 1) Can the TPDV and AMV impact the precipitation over central Asia? If they can, 2) how do the TPDV and AMV modulate the interdecadal variations in central Asian precipitation?

The remainder of the paper is organized as follows. We describe the observational data, model data, and methods in section 2. In section 3, we investigate the impact of TPDV and AMV on central Asian precipitation and related physical processes. Results derived from different models are also compared in section 3. Finally, a summary and concluding remarks are presented in section 4.

2. Data and methods

a. Observation

The monthly precipitation dataset constructed by the Global Precipitation Climatology Centre (GPCC; Schneider et al. 2014)

with a spatial resolution of $1^\circ \times 1^\circ$ from 1891 to 2016 is used. GPCC is chosen as data from more stations are available and this dataset is more suitable to detect the long-term precipitation variations over central Asia compared with other datasets (Trenberth et al. 2014; Hu et al. 2018). The numbers of station observations contributing to each grid are provided along with the precipitation. Based on station availability, GPCC is more reliable during the period of 1955–2004 over central Asia (Fig. 1). The area-averaged central Asian precipitation derived from the precipitation dataset constructed by the Climatic Research Unit (CRU; Harris et al. 2014) is also used for comparison. The correlation coefficient between these two datasets is 0.89 ($p < 0.01$) over central Asia for annual mean precipitation during 1955–2004 (Fig. 2a).

In addition, the Hadley Centre Global Climate Extremes Index 3 (HadEX3) developed through the coordination of the joint World Meteorological Organization (WMO) Commission for Climatology/World Climate Research Programme/Joint Technical Commission for Oceanography and Marine Meteorology (CCl/WCRP/JCOMM) Expert Team on Climate Change Detection and Indices (ETCCDI) is also used. This dataset comprises gridded global land in situ-based dataset of precipitation with a spatial resolution of $1.25^\circ \times 1.25^\circ$ for the period of 1920–2018. At least three stations with valid data are needed within the decorrelation length scale (DLS) for a value to be set for a grid box to ensure that regions with sparse station density will not be influenced by inhomogeneities or other data issues (Dunn et al. 2020).

The tropical Pacific decadal variability (TPDV) index is defined as the leading empirical orthogonal function (EOF) of 9-yr low-pass SST anomalies in the equatorial Pacific (5°S – 5°N) following Zhao and Di Lorenzo (2020). The AMV index is defined as detrended SST anomalies averaged over the North Atlantic (0° – 70°N) following Enfield et al. (2001). The observational TPDV and AMV indices are calculated based on Kaplan SST dataset (Kaplan et al. 1998), and is compared with the results derived from Extended Reconstructed Sea Surface Temperature (ERSST; Huang et al. 2017) in Fig. 2a. The correlation coefficients between these two datasets are 0.97 ($p < 0.01$) and 0.96 ($p < 0.01$) for the TPDV and AMV indices, respectively. For comparison, normalized TPDV and AMV indices are used in this study.

b. Model and experiments

Three sets of experiments were conducted by using the Community Earth System Model version 1.2.0 (CESM1.2) developed by NCAR (Hurrell et al. 2013). The atmospheric component for CESM is the Community Atmosphere Model version 5 (CAM5; Neale et al. 2011) with a horizontal resolution of 1.25° in latitude and 0.9° in longitude, with 26 vertical layers. The oceanic component is the Parallel Ocean Program version 2 (POP2; Smith and Gent 2010) with a horizontal resolution of 1.1° in latitude and 0.27° in longitude in tropics. The longitude gradually increases to 0.54° at 33°N/S and maintains at higher latitudes. The land component is the Community Land Model version 4 (CLM4; Lawrence et al. 2011), and the sea ice component is the Community Ice Code version 4 (CICE4; Hunke and Lipscomb 2008).

FIG. 2. (a) The time series of 9-yr running average of the area-averaged annual mean central Asian precipitation anomaly (black; unit: mm day^{-1}), TPDV index (green; unit: 1), and AMV index (yellow; unit: 1) during 1955–2004. The solid (dashed) black line denotes the central Asian precipitation derived from GPCC (CRU). The solid (dashed) green and yellow lines denote the normalized TPDV and AMV indices derived from Kaplan SST (ERSST). The numbers denote the correlation coefficients between central Asian precipitation derived from GPCC and two indices derived from Kaplan SST and related p values. (b) The time series of 9-yr running average of the annual mean central Asian precipitation anomaly during 1955–2004 (unit: mm day^{-1}) derived from GPCC (black), and the CAP index reconstructed by the observational normalized TPDV and AMV indices derived from Kaplan SST (red). The numbers denote the correlation coefficients between GPCC and reconstructed precipitation index and related p value.

The first set of the experiments is historical simulations (hereinafter HIST), in which model was freely coupled and forced by historical radiative forcing based on phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). The second and third ones are pacemaker-coupled historical simulations that include all forcing identical to the HIST, but with SST restored to the model's climatological mean plus observed historical time-varying anomalies in the tropical Pacific (20°S – 20°N , 175°E – 75°W) and the North Atlantic (0° – 70°N , 70° – 0°W), and referred as HIST-TPAC and HIST-NATL, respectively. For details of the two pacemaker experiments, please refer to Zhou et al. (2016). The HIST, HIST-TPAC, and HIST-NATL simulations are respectively termed historical, hist-resIPO, and hist-resAMO in Zhou et al. (2016). HIST, HIST-TPAC, and HIST-NATL cover the period of 1920–2004, and the first two consist of nine realizations in which the integrations begin with different initial conditions, while the latter has eight realizations. The CESM1.2 can well capture the observed climatological precipitation over central Asia (Fig. 3b). Both HIST-TPAC and HIST-NATL can reasonably reproduce the phase evolution and spatial pattern of

FIG. 3. Climatological annual mean precipitation derived from (a) GPCC, and the historical simulations of (b) CESM1.2 and (c) MRI-ESM2-0 during the period of 1955–2004.

the TPDV and AMV, respectively (Figs. S1 and S2 in the online supplemental material). We use the ensemble mean of HIST-TPAC (HIST-NATL) to investigate the impact of TPDV (AMV) on central Asian precipitation. For HIST-TPAC, while the SST anomalies over the tropical Pacific vary synchronously with the observation, the atmosphere and ocean are freely coupled in other regions and not in the same phase for different members due to different initial conditions. Thus the AMV-related signal and other stochastic noises are greatly suppressed by the multimember ensemble average. It is estimated that the SST variance of the ensemble mean of HIST-TPAC over the North Atlantic is less than 20% of that in the individual members. This also works for HIST-NATL.

In addition, the outputs of the three-member MRI-ESM2-0 that participates the GMMIP are used to verify the results derived from CESM1.2. The MRI-ESM2-0 is developed by the Meteorological Research Institute (MRI) of the Japan Meteorological Agency. This model consists of four component models coupled by Scup, including the atmosphere–land

component MRI-AGCM3.5 with a horizontal resolution of T_{L159} , Model of Aerosol Species in the Global Atmosphere mark-2 revision 4-climate (MASINGAR mk-2r4c), the MRI Chemistry Climate Model version 2.1 (MRI-CCM2.1), and the MRI Community Ocean Model version 4 (MRI.COMv4) (Yukimoto et al. 2019). The MRI-ESM2-0 can also reasonably capture the observed climatological precipitation over central Asia (Fig. 3c).

c. Methods

A 9-yr running average is applied to the observation and model outputs to remove interannual signals. One-dimensional linear regression analysis and multiple linear regression analysis are applied on the low-pass filtered time series of precipitation, AMV, and TPDV indices. A 1000-ensemble Monte Carlo nonparametric method (hereinafter MC test) is used to test the statistical significance at the 99%, 95%, and 90% confidence levels ($p < 0.01$, $p < 0.05$, and $p < 0.1$) of correlation coefficients and regression coefficients of the filtered time series.

To investigate the propagation of wave energy, the wave activity flux is diagnosed. Refer to Takaya and Nakamura (2001), its horizontal components in pressure coordinates are

$$W = \frac{1}{2|\mathbf{u}|} \left\{ \begin{aligned} &\bar{u}(\psi_x'^2 - \psi'\psi_{xx}') + \bar{v}(\psi_x'\psi_y' - \psi'\psi_{xy}') \\ &\bar{u}(\psi_y'\psi_x' - \psi'\psi_{yx}') + \bar{v}(\psi_y'^2 - \psi'\psi_{yy}') \end{aligned} \right\}, \quad (1)$$

where $\mathbf{u} = (u, v)$ denotes the horizontal wind velocity, and ψ denotes the eddy streamfunctions. Overbars and primes denote the mean states and anomalies from the mean states, respectively. Subscript x and y denote zonal and meridional gradient, respectively.

3. Results

a. Observed interdecadal variability of central Asian precipitation

A thorough analysis of the long-term and decadal variations of central Asian precipitation is hampered by the sparse observational precipitation records. Only few stations have long-term observational records more than 100 years, and those are mainly located on the foothills (Fig. 1). Before the 1950s, there were few monthly precipitation observations over central Asia, and the total count of monthly station observations contributing to each grid cell is less than 600 (Fig. 1a). The number of station observation in central Asia has decreased since the 1990s because of the breaking down of the Soviet Union in 1991 (Unger-Shayesteh et al. 2013). Due to the lack of station observational records during the first half of the twentieth century, the gridded observational precipitation dataset is more reliable during 1955–2004, which is the focus period of this study (Fig. 1).

Less precipitation is observed before 1980, following a wetter condition (Fig. 2a). The TPDV index is significantly correlated with the observed central Asian precipitation ($r = 0.52$) at the 10% level. However, Hu et al. (2017) calculated the correlation coefficients between common climate indices and central Asian precipitation for a similar period (1951–2013) and found that the

PDO does not show significant correlation with the annual mean central Asian precipitation. This insignificant correlation is also seen for the interdecadal Pacific oscillation (IPO) index ($r = 0.40$, $p > 0.1$), indicating that the central Asian precipitation may be mainly influenced by the tropical Pacific SST variability. There is no significant correlation between the AMV index and observed central Asian precipitation ($r = 0.32$, $p > 0.1$) during the study period on the interdecadal time scale. The TPDV and AMV are in the same phase during the period of 1962–77, and are out of phase during 1978–97 (Fig. 2a). The effects of TPDV and AMV may overlap or offset each other in different periods because of different phase combinations, obscuring the TPDV- and AMV-related signals in the observed precipitation series.

To obtain the combined effects of TPDV and AMV on central Asian precipitation, we applied the multiple linear regression technique to central Asian precipitation derived from GPCC. The multiple linear regression model for central Asian precipitation is

$$\text{CAP} = 0.0068\text{TPDV_norm} + 0.0035\text{AMV_norm}, \quad (2)$$

where CAP denotes the reconstructed annual mean central Asian precipitation; TPDV_norm and AMV_norm are the normalized 9-yr running average of observational TPDV index and AMV index, respectively. A significant correlation is found between the CAP index and the observation ($r = 0.57$) at the 5% level during 1955–2004, which is higher than the correlation coefficients for the individual TPDV and AMV indices (Fig. 2b). The above results show that the interdecadal variations of observational central Asian precipitation are modulated by the combined effect of TPDV and AMV. The positive signs of the regression coefficients of these two indices indicate that during the positive phase of TPDV and the warm phase of AMV, central Asia receives above-normal precipitation. Thus, we use pacemaker experiments of CESM1.2, which restore observed SST anomalies over the tropical Pacific or North Atlantic, to identify and isolate the contributions of TPDV and AMV on central Asian precipitation in the subsequent analysis.

b. Impact of the TPDV

To separate the contributions of TPDV and AMV on central Asian precipitation, observed SST anomalies are restored in the tropical Pacific (20°S–20°N, 175°E–75°W) and North Atlantic (0°–70°N, 70°W–0°) in the historical simulation of the CESM1.2 model. These experiments are referred as HIST-TPAC and HIST-NATL, respectively (see section 2b). A significant correlation (0.68, $p < 0.01$) is found between the precipitation over central Asia derived from the ensemble mean of the HIST-TPAC and the observational TPDV index (Fig. 4a). The correlation coefficient is higher than that in the observation, partly because the AMV-related anomalies and other stochastic noises are greatly suppressed by the multimember ensemble average. For one standard deviation of the TPDV index, central Asian precipitation increases at a rate of 0.24 (0.18–0.30 for the 95% confidence range) standard deviations (Fig. 4b).

To understand how SST anomalies over the tropical Pacific drive the interdecadal variations in central Asian precipitation,

we regressed SST, SLP, precipitation, and wind anomalies derived from the HIST-TPAC onto area-averaged precipitation over central Asia (Figs. 5a,c). The increase of central Asian precipitation is accompanied with positive SST anomalies over the tropical eastern Pacific and negative SST anomalies over the subtropical western Pacific, which agrees with the positive phase of TPDV (Fig. 5c). Consistent with the distribution of SST anomalies, the SLP anomalies show a seesaw pattern with negative signals over the eastern Pacific and positive signals over the Indo–western Pacific warm pool (Fig. 5c). The southwesterly winds along the northwestern flank of the expansive high SLP over the Indo–western Pacific warm pool can transport more moisture to southeastern central Asia from the Arabian Sea and tropical Africa, leading to the increase of precipitation over this region (Fig. 5a).

The high SLP anomalies over the Indo–western Pacific result from weakened zonal gradient of tropical SSTs in the positive TPDV phase, which is similar to that induced by El Niño on the interannual time scales (Mariotti 2007; Chen et al. 2019). Because of the weakened Walker circulation, convection over the Maritime Continent (central-eastern Pacific) is suppressed (enhanced) (Fig. 6a), leading to a pair of baroclinic Rossby wave responses on both sides of the equator (Fig. 6b). As a result, an anomalous low-level anticyclonic circulation is located over the northern Indian Ocean and the Indian continent (Figs. 5c and 6c), drying South Asia but moistening central Asia (Fig. 5a). In addition, according to previous studies (Barlow and Tippett 2008; Hoell et al. 2013; Barlow et al. 2016; Rana et al. 2019), following the enhanced convective heating over the equatorial central-eastern Pacific (Fig. 6a), there are poleward-propagating equivalent barotropic Rossby wave trains along the great circles on both hemispheres, as evinced by the significant geopotential height anomalies of the same sign at different levels (Figs. 6b,c). Emanating from the central equatorial Pacific, the wave train extends eastward over North America and the North Atlantic into the western Asia. These features are reversed when the SST anomalies in Pacific turns into their negative phase, leading to the recurrent drought events in spring since 1999 over central-southwest Asia (Lyon et al. 2014).

c. Impact of the AMV

We further examine the relationship between central Asian precipitation and the AMV using the HIST-AMV experiments. After removing the TPDV-related responses and statistic noises, a significant correlation (0.70, $p < 0.01$) between central Asian precipitation and the observational AMV index is obtained, indicating that the warm (cold) phase of AMV favors increased (decreased) precipitation over central Asia (Fig. 4c). One standard deviation of the AMV index corresponds to an increase of the central Asian precipitation at a rate of 0.24 (range of 0.18–0.29) standard deviations (Fig. 4d).

The AMV-related precipitation responses are different from those forced by the TPDV (Figs. 5a,b), implying that the SST anomalies over the North Atlantic influence central Asian precipitation in a different way. To investigate the related physical mechanisms, we regressed SST, precipitation, geopotential height, and wind anomalies derived from the HIST-NATL onto

FIG. 4. (a) The time series of 9-yr running average of simulated area-averaged central Asian precipitation anomaly (black; unit: mm day⁻¹) derived from the HIST-TPAC and the observational normalized TPDV index (blue; unit: 1) and (b) their relationship. (c) The time series of 9-yr running average of simulated area-averaged central Asian precipitation anomaly (black; unit: mm day⁻¹) derived from the HIST-NATL and the observational normalized AMV index (blue; unit: 1) and (d) their relationship. The black lines in (a) and (c) denote the results of ensemble mean; the light shades are for plus and minus half of the standard deviation about the ensemble mean. The numbers denote the correlation coefficient between central Asian precipitation and the TPDV and AMV indices and related p values. The red fitting lines in (b) and (d) are obtained by the least squares method based on the normalized precipitation anomaly and normalized TPDV and AMV indices. Blue and gray dashed curves denote the 95% confidence range and prediction range of the linear regression, respectively. The numbers denote the regression coefficients and 95% confidence ranges.

area-averaged precipitation over central Asia (Figs. 5b,d and 7). The positive precipitation anomalies over central Asia derived from the HIST-NATL accompany the warm phase of AMV, showing a basinwide warming in the North Atlantic (Fig. 5d). The positive SST anomalies over the North Atlantic can result in an eastward barotropic zonal wave train located along the Northern Hemisphere westerly jet with positive centers over western Europe and the North Pacific, and negative centers over the high-latitude North Atlantic and central Asia (Fig. 5d). This zonal wave train is evident in both upper troposphere and lower troposphere, and intensifies with height (Fig. 7).

The barotropic stationary wave pattern dynamically corresponds to an anomalous cyclone at low-level troposphere over northern central Asia (Fig. 5d). Moisture from the North Atlantic and northern Europe is transported into northern central Asia by strengthened westerlies along the southern flank of the cyclonic circulation, leading to an increase of precipitation over central Asia, especially the northern part (Fig. 5b). In addition, the wave train interacts with the mean mid- and upper-level tropospheric westerly jet flows, resulting in a strengthened ascending motion over northern central Asia. The southerlies along the eastern flank of the anomalous

cyclonic circulation can result in warm advection, which favors an anomalous ascending motion and increased precipitation over northern central Asia (Fig. 5d). This teleconnection pattern is similar to the AMV-related interdecadal circumglobal teleconnection pattern over the range of North Atlantic to central Asia (Wu et al. 2016; Si and Ding 2016).

d. Comparison of different model simulations

Our results derived from CESM1.2 provide a comprehensive picture of how the TPDV and AMV impact central Asian precipitation. We further confirmed the results with MRI-ESM2-0 to avoid model dependence. In MRI-ESM2-0, significant correlation coefficients between TPDV/AMV indices and central Asian precipitation under related experiments ($r = 0.84$ and 0.66 for HIST-TPAC and HIST-NATL, respectively; $p < 0.01$ for both) strongly supports our results based on CESM1.2 (Fig. 8). Besides, the physical processes are also significant in MRI-ESM2-0 although there are some discrepancies (Fig. 9). For example, the precipitation signals are strong and significant over the whole of central Asia both for the TPDV and AMV (Figs. 9a,b). The precipitation-related negative SST anomalies are weaker and insignificant over the western Pacific but stronger over the North Atlantic in the

FIG. 5. The annual mean precipitation (shading; unit: mm day^{-1}) and vertical integrated moisture fluxes (vectors; unit: kg m s^{-1}) regressed onto the area-averaged annual mean central Asian precipitation (unit: mm day^{-1}) in (a) HIST-TPAC and (b) HIST-NATL. (c) The annual mean sea surface temperature (shading; unit: K), sea level pressure (contours; unit: Pa), and 850-hPa wind anomalies (vectors; unit: m s^{-1}) regressed onto the area-averaged annual mean central Asian precipitation in the HIST-TPAC. (d) The annual mean sea surface temperature (shading; unit: K), 200-hPa geopotential height anomalies relative to the zonal mean (contours; unit: m), and 700-hPa wind anomalies (vectors; unit: m s^{-1}) regressed onto the area-averaged annual mean central Asian precipitation in the HIST-NATL. The white hatched patterns indicate that the regression coefficients are significant at the 10% level using the MC test. The regression coefficients of moisture fluxes and wind anomalies shown are significant at the 10% level using the MC test. All variables are derived from the ensemble mean of HIST-TPAC or HIST-NATL of CESM1.2.

FIG. 6. The annual mean (a) precipitation (unit: mm day^{-1}), (b) 200-hPa geopotential height anomalies relative to the zonal mean (unit: m) and 200-hPa wind (vectors; unit: m s^{-1}), and (c) 850-hPa streamfunction (unit: $10^7 \text{ m}^2 \text{ s}^{-1}$) relative to the zonal mean and 850-hPa wind (vectors) regressed onto the area-averaged annual mean central Asian precipitation in the HIST-TPAC. The white hatched patterns indicate the regression coefficients are significant at the 10% level using the MC test. All variables are derived from the ensemble mean of HIST-TPAC of CESM1.2.

HIST-TPAC (Fig. 9c). Besides, the AMV-induced wave train is different with CESM1.2 over East Asia (Fig. 9d). These discrepancies may due to fewer members of MRI-ESM2-0, which could make the TPDV (AMV)-related responses not be thoroughly removed from the ensemble mean of the HIST-NATL (HIST-TPAC) experiments. In addition, the uncertainties of the atmospheric responses to the AMV-related SST anomalies in different models may come from the atmospheric internal variability, which is related with the interactions between the transient eddy and large-scale flow (Lin et al. 2016).

FIG. 7. The annual mean (a) 200-, (b) 500-, and (c) 700-hPa geopotential height anomalies relative to the zonal mean (unit: m) regressed onto the area-averaged annual mean central Asian precipitation (unit: mm day^{-1}); (a) also includes the corresponding wave-activity fluxes (vectors) in the HIST-NATL. The white hatched patterns indicate the regression coefficients are significant at the 10% level using the MC test. All variables are derived from the ensemble mean of HIST-NATL of CESM1.2.

4. Summary and concluding remarks

In this study, we investigate the influences of TPDV and AMV on the interdecadal variations of central Asian precipitation based on pacemaker experiments of the CESM1.2 and MRI-ESM2-0 models that restore the historical observational SST anomalies in the tropical Pacific and North Atlantic. We analyzed the physical processes related to the TPDV and

FIG. 8. As in Figs. 4a and 4c, but derived from MRI-ESM2-0.

FIG. 9. As in Fig. 5, but derived from MRI-ESM2-0.

AMV. The major results are summarized in Fig. 10 and given below.

The TPDV plays a dominant role in driving the interdecadal variations in central Asian precipitation. The positive phase of TPDV can lead to an increase of precipitation over central Asia, especially the southeastern region. The negative SST anomalies in the western Pacific are associated with high SLP over the Indo-western Pacific warm pool; the southwesterly fluxes along the northwestern flank of the high SLP can bring

more water vapor to southeastern central Asia and lead to the increase of precipitation (Fig. 10a). The positive SST anomalies in the tropical eastern Pacific can induce a weakened Walker circulation, which is associated with a decrease of precipitation over the western Pacific, an increase of precipitation over the central eastern Pacific, and related changes in latent heat release. Both the poleward-propagating equivalent barotropic Rossby wave trains emanating from the central equatorial Pacific and the westward-propagating baroclinic

FIG. 10. Schematic diagram of the effect of (a) TPDV and (b) AMV on the interdecadal variability in central Asian precipitation. The red and blue shading denotes the positive and negative SST anomalies, respectively; green shading denotes the positive precipitation anomalies over central Asia. (a) The red curve denotes the range of anomalous high sea level pressure, the blue arrow denotes the anomalous low-level anticyclonic circulation, and the black arrows denotes the wave responses. (b) The blue L and red H denote the anomalous upper-level low and high geopotential heights, respectively.

Rossby wave trains emanating from the western Pacific can influence precipitation over southeastern central Asia.

The AMV can also modulate the interdecadal variations in precipitation over central Asia. A warmer North Atlantic can lead to wetter conditions over central Asia, especially the northern part. The positive phase of AMV can induce an eastward circumglobal stationary baroclinic wave train located along the Northern Hemisphere westerly jet, with positive centers over western Europe and the North Pacific and negative centers over the North Atlantic and central Asia (Fig. 10b). The trough node to the west of central Asia favors the ascending motion over northern central Asia and an increase of precipitation over this region. Moisture from the North Atlantic and northern Europe is transported into northern central Asia by strengthened westerlies along the southern flank of the anomalous cyclonic circulation.

When SST anomalies over the tropical eastern Pacific and North Atlantic are in the same phase, the precipitation responses are enhanced compared with those forced by SST anomalies over the tropical Pacific or North Atlantic individually. The TPDV and AMV are in the same phase during 1962–77, but are out of phase during 1978–97, resulting in the low correlation between the observational central Asian precipitation and the TPDV and AMV indices individually since 1950s. Based on the observational TPDV and AMV indices, we successfully reconstruct the historical precipitation in central Asia, which is significantly correlated ($r = 0.57$, $p < 0.05$) with

the observation. We also extend the study period using HadEX3, finding a significant correlation coefficient ($r = 0.55$, $p < 0.01$) between central Asian precipitation derived from HadEX3 and the CAP index calculated based on the observational TPDV and AMV indices during 1920–2018 (Fig. 11). The relationship between central Asian precipitation and both TPDV and AMV is robust at a longer time period.

Our study shows how the TPDV and AMV influence central Asian precipitation (Fig. 10). The westward-propagating

FIG. 11. The time series of 9-yr running average of annual mean central Asian precipitation anomaly during 1920–2018 (unit: mm day^{-1}) derived from HadEX3 (black) and reconstructed based on the observational normalized TPDV and AMV indices derived from Kaplan SST (red). The numbers denote the correlation coefficient between HadEX3 and the reconstructed precipitation index and related p value.

baroclinic Rossby wave train, the eastward-propagating barotropic Rossby wave train, and the anomalous low-level circulation associated with the anomalous SLP all favor more precipitation over central Asia in the positive phase of the TPDV. But which mechanism is the primary factor remains unknown. Further efforts (e.g., sensitivity experiments) should be devoted to understanding and distinguishing the relative contributions of different processes related to the TPDV-induced precipitation signals.

Given the evidence that the TPDV and AMV are the main drivers of the interdecadal variations of central Asian precipitation, this raises the possibility of predicting overall trends in central Asian precipitation in the next few decades. If both the TPDV and AMV shift from negative phase to positive phase, an increase of precipitation will be observed over central Asia. If the TPDV and AMV change out of phase (e.g., the TPDV shifts from negative phase to positive phase and the AMV shifts from positive to negative), central Asian precipitation will increase at a smaller rate. The TPDV has shifted into its cold phase since the 2000s and has turned into a warm phase in recent years (Meehl et al. 2016). The AMV has been in its warm phase since the mid-1990s, and which may last for 25–40 years based on the span of its prior warm phase (Lin et al. 2019). Thus, central Asia is anticipated to receive above-normal precipitation in the next decade without considering the influences of other forcings. Better understanding of the physical processes that drive the interdecadal variations is necessary for policymakers to formulate effective adaptation and mitigation strategies, especially for central Asia where the economy highly relies on agriculture and the ecosystem is highly sensitive to changes in precipitation (Varis 2014; Jiang et al. 2017).

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Data availability statement. GPCC precipitation and Kaplan SST data were provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their website at <https://psl.noaa.gov/data/gridded/data.gpcc.html> and https://psl.noaa.gov/data/gridded/data.kaplan_sst.html, CRU precipitation data are available at <https://catalogue.ceda.ac.uk/uuid/89e1e34ec3554dc98594a5732622bce9>. HadEX3 is available at <https://www.metoffice.gov.uk/hadobs/hadex3/>. ERSST can be downloaded from NOAA National Centers for Environmental Information at <https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v5>. The results of MRI-ESM2-0 are available at <https://esgf-node.llnl.gov/search/cmip6/>. The results of CESM1.2 are available on request from zhoutj@lasg.iap.ac.cn.

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