Moisture Sources Associated with Precipitation during Dry and Wet Seasons over Central Asia

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ABSTRACT

Identifying the origin of moisture is a key process in revealing the formation mechanisms of precipitation, but the moisture sources for central Asia have not been well documented in previous studies. In this work, we employ the Lagrangian model FLEXPART over 2011–19 to address this question. Multiple observational products indicate that the times of dry and wet seasons are opposite for western and eastern central Asia bounded by 75°E. The wet season is November–April (NDJFMA) for western central Asia but May–October (MJJASO) for eastern central Asia, while the opposite is true for the dry season. The main moisture source regions for western central Asia are local regions (with a contribution of 49.11%), western Eurasia (21.47%), and western Asia (11.37%) during MJJASO and local regions (33.92%), western Asia (27.50%), and western Eurasia (17.60%) during NDJFMA. For eastern central Asia, moisture mainly originates from local regions (52.38%), western central Asia (25.22%), and northern Eurasia (9.26%) during MJJASO and western central Asia (30.86%), local regions (30.82%), western Asia (10.31%), and western Eurasia (10.26%) during NDJFMA. The differences in moisture sources between dry and wet seasons mainly occur in local regions and western Asia for western central Asia but in local regions for eastern central Asia. The moisture from northern Eurasia, western Eurasia, and western central Asia is transported into target regions by the westerly and southwesterly winds that are associated with a deep low trough over central Asia. Moisture is transported from western Asia by the anticyclone occurs over North Africa and western Asia in the lower and middle troposphere.

1. Introduction

The arid and semiarid central Asia area is located in the interior of Eurasia, connecting the cultural and economic exchange between Europe and Asia (Fig. 1). The land-

cover types in this region, which are characterized by scarce water with an annual total precipitation less than 300 mm, are dominated by vast barrenness and sparse vegetation, implying a fragile ecosystem that is highly vulnerable to climate change (IPCC 2013; Huang et al. 2016, 2017; Hu et al. 2017; Peng et al. 2020). The safety of this ecosystem and the sustainable development of society in this region are closely affected by changes in regional precipitation, which is the key component of local water resources. Understanding the physical mechanisms that are responsible for precipitation changes in central Asia is important for both climate change adaption activities and policymaking.

The occurrence of a rainfall event is associated with an abundant supply of water vapor and rising motions; the

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FIG. 1. Distribution of the land cover types and definitions of the geographical regions: Central Asia (35° – 55° N, 50° – 95° E), the North Atlantic Ocean (N. Atlantic: 20° – 60° N, 80° W– 0°), northern Eurasia (N. Eurasia: 55° – 80° N, 5° – 110° E), North Africa (N. Africa: 10° – 35° N, 0° – 30° E), western Asia (W. Asia: 10° – 35° N, 30° – 60° E), the Indian subcontinent (Indian Sub.: 0° – 35° N, 60° – 100° E), and western Eurasia (W. Eurasia: 35° – 55° N, 0° – 50° E). The vertical white dashed line indicates 75° E. The 18 land-cover types are water bodies (WB), evergreen needleleaf forest (EN), evergreen broadleaf forest (EB), deciduous needleleaf forest (DN), deciduous broadleaf forest (DB); mixed forest (MF), closed shrublands (CS), open shrublands (OS), woody savannas (WS), savannas (Sa), grasslands (Gr), permanent wetlands (PW), croplands (Cr), urban and built-up (UB), cropland/natural vegetation mosaic (CN), permanent snow and ice (PS), barren or sparsely vegetated (BS), and unclassified (Un).

water vapor mainly results from local evaporation and moisture advection from remote regions (Trenberth et al. 2003; Li et al. 2016). The relationship between moisture transport and precipitation changes over central Asia at different time scales has been documented in previous studies (Shi et al. 2007; Li et al. 2008; Ren et al. 2016). At a long-term mean time scale, the water vapor from four moisture flux divergence centers (the Atlantic Ocean, Arctic Ocean, Black Sea, and Caspian Sea) can be transported into central Asia following the prevailing westerlies (Li et al. 2008). Local evaporation from glacial meltwater, river runoff, soils, and vegetation also plays an important role in favoring precipitation over central Asia (Shi et al. 2007; Ren et al. 2016).

The precipitation in central Asia also shows obvious interannual variation, which is determined by changes in moisture flux that are associated with the Asian summer subtropical westerly, South Asian high, dynamic and thermodynamic effects of the Tibetan Plateau, and circumglobal teleconnection patterns (Wu and Qian 1996; Qian et al. 2001; Ding and Wang 2005; Ding et al. 2011; Chen and Huang 2012; Zhao et al. 2014; Huang et al. 2015; Wei et al. 2017). Against the background of global warming, the precipitation in central Asia has significantly changed, with an increasing trend in the northern and eastern regions during the past half-century (Chen et al. 2011; Hu et al. 2017). Notably, the climate in northwest China (located in eastern central Asia) has shifted from warm and dry to warm and wet because of increased moisture from both more

local evaporation and the southward displacement of the Asian subtropical westerly jet in response to global warming (Shi et al. 2007; Peng and Zhou 2017; Peng et al. 2018).

The above studies that addressed the relationship between precipitation variations and moisture transport were based on analyses over a conventional Eulerian grid. This method can adequately describe moisture pathways that are associated with precipitation but cannot assess changes in atmospheric moisture over specific regions because of the fast transition of the wind field (Stohl et al. 2005; Sodemann et al. 2008). Consequently, the contributions from moisture sources that are associated with precipitation over study areas cannot be accurately quantified (Sodemann et al. 2008; Sun and Wang 2014).

A method that is based on a Lagrangian model has an advantage in identifying the geographical origins of moisture (Stohl and James 2004; Gimeno et al. 2010). This method can simulate the trajectories of air particles back in time to trace their origins or forward in time to infer their diffusion (Stohl et al. 2005). Based on an analysis of changes in specific humidity along the trajectories of target air particles, moisture that evaporates into or precipitates out from the atmosphere can be detected. Therefore, the geographical origins of moisture and their quantitative contributions can be identified. This method has been widely used in many studies to address the moisture sources that are associated with precipitation at both the global and regional

scales (Stohl and James 2004; Nieto et al. 2006; Sodemann et al. 2008; Vázquez et al. 2016).

In Asia, many studies focused on precipitation over monsoon regions to address moisture sources based on Lagrangian models. Bohlinger et al. (2017) applied a Lagrangian model to reveal the moisture sources for extreme precipitation that was associated with the low pressure system in Nepal. Meanwhile, this Lagrangian method has also been used to reveal the moisture sources of precipitation in many regions over East Asia, including Changjiang-Huaihe, the arid and semiarid grassland, Sichuan Basin, the Loess Plateau, South China, and North China (Jiang et al. 2013; Sun and Wang 2014; Huang and Cui 2015; Li et al. 2016; Jiang et al. 2017; Huang et al. 2018; Hu et al. 2018). Moisture source detection studies for the arid central Asia area are scarce and mainly focused on the summer precipitation in northwestern China, which revealed that local evaporation and moisture transport from Eurasia are the dominant sources and the interdecadal variation of precipitation was largely influenced by moisture from the land to the southwest and northwest (Hua et al. 2017; Wang et al. 2017).

However, the moisture sources that are associated with seasonal precipitation and the quantitative contributions over central Asia remain unclear. Based on multiple observational products, the precipitation in central Asia shows obvious annual variations, but the time of the dry and wet seasons are the opposite for eastern and western central Asia, which are bounded by 75°E. Therefore, we employ FLEXPART to assess the contributions from moisture source regions that are associated with precipitation in the dry and wet seasons for eastern and western central Asia. In this study, we show evidence that the local water cycle and moisture from Eurasia play an important role in the precipitation over both eastern and western central Asia but with obvious differences in terms of the quantified contributions between the dry and wet seasons.

We organize the remainder of this work as follows. In section 2, we introduce the observations and reanalysis datasets and describe the moisture source detection method based on a Lagrangian model. In section 3, we show the back-trajectory analyses from this Lagrangian model. Finally, we summarize the main results in section 4.

2. Data and methods

a. Data description

The datasets that were used in this study are as follows:

- 1) The Global Precipitation Climatology Project (GPCP) version 1.3 daily precipitation at a horizontal resolution of $1^\circ \times 1^\circ$, which covers the period from October 1998 to the present (Huffman et al. 2001). This dataset was derived from the optimally merged estimation of international satellite data and precipitation-gauge analyses, which is archived at <https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-daily/access/>.
- 2) The monthly mean precipitation Climate Research Unit (CRU) Time Series version 4.0.3, which was derived from the interpolation of worldwide station data and covers the period from 1901 to 2018 at a horizontal resolution of $0.5^\circ \times 0.5^\circ$ (Harris et al. 2020). This dataset is available at <https://catalogue.ceda.ac.uk/uuid/10d3e3640f004c578403419aac167d82>.
- 3) The Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis version 8.0, which was derived from quality-controlled worldwide stations (including GHCN V2, station bases for CRU, the Food and Agriculture Organization of the United Nations, and 190 countries' stations from national meteorological and/or hydrological services) with a record duration of no less than 10 years (Schneider et al. 2015). This dataset has a horizontal resolution of $0.5^\circ \times 0.5^\circ$ and covers the period from 1891 to 2016. This dataset is available from <https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html>.
- 4) The International Satellite Land Surface Climatology Project Initiative II (ISLSCP II) data collection 4 MODIS Land Cover Product (Friedl et al. 2010). This dataset covers the period from October 2000 to October 2001, available at https://daac.ornl.gov/ISLSCP_II/guides/modis_landcover_xdeg.html.
- 5) The 6-hourly Climate Forecast System Reanalysis (CFSR) version 2 from National Centers for Environmental Prediction (NCEP), which has a horizontal resolution of $0.5^\circ \times 0.5^\circ$ and covers the period from 2011 to the present (Saha et al. 2014). The used variables are dewpoint temperature, geopotential height, land cover, planetary boundary layer height, pressure, relative humidity, temperature, water equivalent of accumulated snow depth, and horizontal and vertical wind fields. This dataset can be retrieved from <https://rda.ucar.edu/datasets/ds094.0/>.
- 6) The daily NCEP–NCAR Reanalysis 1, which has a horizontal resolution of $2.5^\circ \times 2.5^\circ$ and covers the period from 1949 to the present (Kalnay et al. 1996). This dataset is from <https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>.

b. Model simulation

To accurately determine the moisture sources that are associated with precipitation over central Asia, the Lagrangian model FLEXPART v9.2, which was developed by the Norwegian Institute for Air Research, was employed in this work (Stohl et al. 2005). This model can

simulate the trajectories of air particles back in time to track their origins or forward in time to address their diffusion and can be used to study the long-distance transport of air pollution. The evaporation minus precipitation budget can be identified by analyzing changes in the specific humidity along the trajectories of air particles, which can accurately reflect the moisture source or sink regions. Thus, this model has been widely used in previous studies on hydrological cycles to track moisture pathways that are associated with precipitation over various regions worldwide (Stohl and James 2004; Nieto et al. 2006; Sodemann et al. 2008; Gimeno et al. 2010; Drumond et al. 2011; Sun and Wang 2015; Läderach and Sodemann 2016; Vázquez et al. 2016; Bohlinger et al. 2017).

In this study, we performed a FLEXPART simulation that was driven globally by the CFSR dataset forward in time during the period 2011–19. This simulation was run with 6-h time steps. We used “domain-fill” mode, and one million particles were released to equally split the entire global atmosphere, so the mass of each air particle was the same. The variables of each air particle (latitude, longitude, level above ground, specific humidity, and air mass, among many others) were saved at 6-h time intervals.

c. Moisture source detection method

Moisture changes in a particle during a certain time interval are the result of evaporation into or precipitation out from the air particle. For each air particle, the change in specific humidity at time t can be expressed as

$$e - p = m \frac{\Delta q}{\Delta t}. \quad (1)$$

Here, the evaporation, precipitation, and air mass are denoted by e , p , and m , respectively. The changes in specific humidity q from time $t - 6\text{ h}$ to t are expressed as $\Delta q = q_t - q_{t-6\text{ h}}$. The time interval Δt was set as 6 h in this study. The evaporation minus precipitation ($e - p$) over specific regions can be identified based on Eq. (1). By analyzing changes in the specific humidity along the back-trajectories, a region with $e - p > 0$ ($e - p < 0$) is regarded as a moisture source (moisture sink) region.

When reaching the target region from the moisture uptake location, the moisture of an air particle may increase or decrease because of evaporation or precipitation processes. Thus, the moisture contribution from the original uptake location to precipitation in the target region is reduced. To accurately quantify the contributions from different source regions, the moisture source attribution method from Sodemann et al. (2008) was used in this study. This method can be expressed as follows:

- 1) The air particles that precipitate ($q_{\text{release}} = q_{t=-6\text{ h}} - q_{t=0} > 0$) at the beginning time ($t = 0$) over the study region are selected to be tracked backward. All the target air particles are tracked backward for 10 days ($t = -240\text{ h}$), which is the mean residual time of moisture in the atmosphere (Trenberth 1998; Numaguti 1999).
- 2) For each back-trajectory, the moisture uptake location is identified if $e - p > 0$ over the time interval ($t - 6\text{ h}$, t). The water content (the product of the specific humidity and air mass) uptake from this location is denoted as Q_{take}^k for the k th air particle trajectory. Afterward, this air particle is continued back in time until the end of the trajectory or the moisture of the air particle falls out through precipitation. When reaching forward into the target area from source regions, air particles may undergo multiple cycles of evaporation and precipitation to release or uptake moisture over intermediate regions. Thus, the available water uptake from the source region that is contributed to the study region will be updated circularly forward in time in these intermediate regions, with $Q_{\text{take}}^k = Q_{\text{take}}^k$ at a location of $e - p > 0$ but $Q_{\text{take}}^k = Q_{\text{take}}^k + Q_{\text{take}}^k (e - p/Q)$ at a location of $e - p < 0$. Several moisture regions can be identified from one back-trajectory, so the moisture uptake from the identified source region is the sum of all the selected trajectories.
- 3) The contribution from the i th source region (CR_i) can be quantified as

$$\text{CR}_i = \frac{\sum_{k=1}^{k_{\text{tot}}} Q_{\text{take}}^k(i)}{\sum_{k=1}^{k_{\text{tot}}} Q_{t=-6\text{ h}}} \times 100\%. \quad (2)$$

Here, $\sum_{k=1}^{k_{\text{tot}}} Q_{\text{take}}^k(i)$ is the sum of the available moisture uptake for all the target air particles from the i th source region, while $\sum_{k=1}^{k_{\text{tot}}} Q_{t=-6\text{ h}}$ is the total water content of all the selected air particles at 6 h before reaching the study regions.

d. Data processing method

The observed annual cycle of climatological zonal mean precipitation during 2011–16 over central Asia was shown in Fig. 2. To avoid uncertainties from data dependency, we examined the results based on three observed datasets (GPCP, GPCC, and CRU). The observed zonal mean monthly total precipitation over central Asia ranged from less than 2 mm to larger than 50 mm, demonstrating an obvious shift from the dry season to the wet season (Figs. 2a,c,e). The time of the

FIG. 2. Annual cycle of the climatological zonal mean precipitation over central Asia during 2011–16. Results from (a),(b) GPCP, (c),(d) GPCC, (e),(f) CRU, and (g),(h) CFSR. Columns indicate (left) the monthly total precipitation (unit: mm month^{-1}) and (right) the corresponding percentage (relative to the annual total precipitation, unit: %).

dry (wet) season was different between the regions to the west and east of 75°E , referred to as western and eastern central Asia, respectively. In eastern central Asia, the wet season occurred in May–October (MJJASO) and the dry season occurred in November–April (NDJFMA). However, the wet season in western central Asia occurred in NDJFMA and the dry season occurred in MJJASO, showing the opposite result. GPCP showed the largest

precipitation amount over central Asia, followed by CRU and GPCC. The regional characteristics of the precipitation annual cycle over central Asia could be clearly observed in terms of the ratio of the monthly total precipitation to the annual total (Figs. 2b,d,f). The seasonal evolution of the observed monthly precipitation in both western and eastern central Asia was adequately captured by CFSR despite the overestimated precipitation

amount (Figs. 2g,h). These have been verified by the results derived from longer periods (see Fig. S1 in the online supplemental material).

Considering the regional and seasonal characteristics in the above results, the moisture sources that were associated with precipitation over central Asia were studied separately in the dry and wet seasons for both the western and eastern regions. Thus, four types (2 seasons $\times$ 2 regions) were classified. For each type, the time series of the area-weighted regional averaged precipitation during 2011–19 was calculated based on the GPCP daily dataset and sorted in decreasing order. Then, the top 90 daily precipitation events were selected as the target events for each type. In total, 360 (90 $\times$ 2 seasons $\times$ 2 regions) daily precipitation events in central Asia were selected.

The selected events were not evenly distributed in each month for western and eastern central Asia during both MJJASO and NDJFMA (Fig. S2). These events occurred more in February, March, May, and October for western central Asia, and in June, July, August, November, and December for eastern central Asia. There were large extreme events lasting more than 2 consecutive days among the selected daily events for western and eastern central Asia during both MJJASO and NDJFMA (Fig. S3). In addition, there were 16 overlapping days for the selected daily events between western and eastern central Asia, with 9 days in NDJFMA and 7 days in MJJASO.

The mean precipitation of target events for western and eastern central Asia was 2.49 and 2.86 mm day⁻¹ during MJJASO and 5.03 and 2.3 mm day⁻¹ during NDJFMA, respectively. The mean precipitation events for western central Asia during NDJFMA were more intense than the other three types (which are with comparable magnitudes). In terms from the spatial distributions, the mean magnitudes of selected precipitation events decreased during MJJASO but increased during NDJFMA from north to south for western central Asia, whereas they decreased from northwest to southeast during both MJJASO and NDJFMA for eastern central Asia (Fig. S4). The observed spatial patterns of selected precipitation events for both western and eastern central Asia can be well reproduced by CFSR despite the under- or overestimated magnitude (Fig. S4).

The CFSR dataset had a 6-h time interval in this study. Thus, for each target daily precipitation event, the corresponding trajectories were tracked backward at 4 times (0000, 0600, 1200, and 1800 UTC) on the day of the precipitation event. The backward-tracing time was set as 10 days, which is the mean lifetime of atmospheric moisture (Trenberth 1998; Numaguti 1999). The outputs were at a 6-h time interval. As a result, the target particles were tracked backward from the starting time ($t = 0$) to 10 days prior ($t = -240$ h). Day 1 (for back-tracked

results) was from $t = -6$ h to $t = -24$ h, and day 10 was from $t = -222$ h to $t = -240$ h. Day 3–1 was the sum of days 1, 2, and 3, (i.e., from $t = -6$ h to $t = -72$ h). The k -means clustering algorithm from Arthur and Vassilvitskii (2007) was employed to analyze the trajectories of the target air particles. For each type, all the target air particles were first merged and then cluster analysis was done by setting the cluster number as 50. The cluster analysis was only used to show the general information of moving trajectories for target air particles. The latter figures (after Fig. 4) were derived from all the target trajectories.

3. Results

a. Back-trajectories of air particles that reached central Asia

In this study, we first discussed the results for western central Asia and thereafter for eastern central Asia.

The cluster mean trajectories of target air particles that reached central Asia from starting locations 10 days prior were shown in Fig. 3. As the tropopause over central Asia was around 12 000 m above mean sea level, the lower and middle troposphere in this study were below 4000 and about 4000–8000 m, respectively (figures not shown). During MJJASO (the local dry season), the air particles that reached western central Asia were mainly transported by a westerly from the middle troposphere of North America, the middle and lower troposphere of the North Atlantic Ocean and western Eurasia, and the lower troposphere of northern Eurasia (Fig. 3a). Additionally, air particles from lower troposphere of western Asia and the middle troposphere of North Africa can also arrive at western central Asia.

During NDJFMA (the local wet season), the air particles that reached western central Asia were mainly from the middle to lower troposphere of North America, the North Atlantic Ocean, western Eurasia, and North Africa, and the lower troposphere of northern Eurasia and western Asia. Compared with the MJJASO results, the altitudes of air particles were lower during NDJFMA (Fig. 3c). Furthermore, the numbers of air particles originated from western Asia and northern Eurasia were larger during NDJFMA than that during MJJASO.

For eastern central Asia (Figs. 3b,d), the distributions of the trajectories for the target air particles in both MJJASO and NDJFMA were similar to the results for western central Asia, which were also mainly from North America, the North Atlantic Ocean, northern Eurasia, western Eurasia, North Africa, and western Asia. However, there were still some differences. The altitudes of air particles were much higher for eastern than for western central Asia. For instance, the MJJASO

FIG. 3. Cluster mean trajectories of air particles that reached the target regions. The cluster number is 50, and the asterisks indicate the initial locations 10 days prior: (a) WCA_MJJASO [MJJASO in western central Asia (WCA); black box; 35°–55°N, 50°–75°E], (b) ECA_MJJASO [MJJASO in eastern central Asia (ECA); black box; 35°–55°N, 75°–95°E], (c) WCA_NDJFMA (NDJFMA in western central Asia), and (d) ECA_NDJFMA (NDJFMA in eastern central Asia). “Dry” and “Wet” in the parentheses indicate the local dry and wet season, respectively. The shading indicates the elevation (unit: m MSL).

air particles reaching into eastern central Asia were mainly from the middle troposphere of those regions, higher than the results for western central Asia. Additionally, some air particles from the middle troposphere of the Indian subcontinent and the lower troposphere of the Indian Ocean can arrive in eastern central Asia across the Tibetan Plateau during MJJASO (Fig. 3b).

The moisture that was associated with precipitation in central Asia was mainly transported by atmospheric circulations in the lower and middle troposphere (Fig. 3). Thus, the spatial distributions of the composite mean horizontal winds and geopotential height that were associated with target precipitation events at 700 and 500 hPa are further examined (Fig. 4). In association with the precipitation events in both western and eastern central Asia during MJJASO and NDJFMA, a deep low trough existed to the west of the target region, which extended from 700 to 500 hPa. Thus, the moisture from western and northwestern Eurasia was mainly transported by a westerly and northwesterly/southwesterly that was associated with this low trough into the target region during both MJJASO and NDJFMA.

The moisture from western Asia and North Africa was closely associated with an anticyclone that extends from northern Africa to western Asia. For both western and eastern central Asia, the anticyclone occurred at 700 and 500 hPa, but its intensity varies with the season. During MJJASO, the moisture over western Asia was directly transported into western central Asia by a southwesterly to the northeast of the anticyclone. The moisture over North Africa was first transported into the northern part of western Asia by the westerly to the north of the anticyclone, and then into western central Asia by the southwesterly to the northeast of the anticyclone. The results for western central Asia during NDJFMA were similar to that during MJJASO, but with a larger magnitude of the southwesterly to the northwest of the anticyclone.

For eastern central Asia during MJJASO, the moisture from North Africa and western Asia was first transported into the west region of western central Asia, but then transported southward to the region south of central Asia by the northerly to the east of the anticyclone (Figs. 4e,f,g,h). Thus, few air particles from

FIG. 4. Composite-mean atmospheric circulations for all the target precipitation events at (left) 700 and (right) 500 hPa. Results are shown for (a),(b) WCA_MJJASO, (c),(d) WCA_NDJFMA, (e),(f) ECA_MJJASO, and (g),(h) ECA_NDJFMA. The color shading indicates the geopotential height (unit: m), and the vectors indicate the horizontal wind (unit: m s^{-1}). Gray shading indicates the regions higher than 3000 m MSL.

western Asia and North Africa can reach into eastern central Asia (Fig. 3b). During NDJFMA, however, the region to the north of western Asia was dominated by the westerly and southwesterly. Thus, the moisture from North Africa and western Asia can be transported into eastern central Asia by the atmospheric circulations associated with both the anticyclone and low trough.

Figure 5 shows the changes in specific humidity along the cluster mean trajectories of the target air particles. The specific humidity of the air particles was larger in

the lower troposphere, or inversely proportional to the altitude. After reaching the target regions, the specific humidity of the air particles greatly changed along the trajectories. For western central Asia in MJJASO, the specific humidity of the target air particles from the middle troposphere over North America (the Atlantic Ocean) was initially around 2.6 (3.5) g kg^{-1} and then decreased by less than 1.1 (1.7) g kg^{-1} because of rain when reaching the target area, as seen in Fig. 5a. The specific humidity of air particles from the lower

FIG. 5. Changes in the specific humidity along the trajectories: (a) WCA_MJJASO, (b) ECA_MJJASO, (c) WCA_NDJFMA, and (d) ECA_NDJFMA. The shading indicates the specific humidity (unit: g kg^{-1}).

troposphere of western Asia (4.1 g kg^{-1}) decreased by less than 2.9 g kg^{-1} after reaching western central Asia. In contrast, the specific humidity of air particles from northern Eurasia increased from 2 to larger than 3.5 g kg^{-1} . This was due to vegetation over Eurasia contributing moisture to the lower layers.

Compared to the MJJASO results, the mean specific humidity and corresponding changes in the air particles that reached western central Asia from both the middle and lower troposphere of regions to the west during NDJFMA were smaller (Fig. 5c). The specific humidity of air particles from western Asia decreased from above 5 to less than 2.9 g kg^{-1} because of rain. Note that these may be associated with the forced updrafts induced by complex topography. The specific humidity of air particles from northern Eurasia slightly changed along the trajectories, with a relatively stable value from 0.5 to 0.8 g kg^{-1} .

Upon reaching eastern central Asia during MJJASO, the specific humidity of air particles from North America, the North Atlantic Ocean, and western Asia decreased but the specific humidity of air particles from northern Eurasia increased, similarly to the results for western central Asia (Fig. 5b). During NDJFMA, the changes in the specific humidity of air particles along trajectories for

eastern central Asia were similar to those for western central Asia, with a decrease for North America, the North Atlantic Ocean, western Eurasia, and western Asia (Fig. 5d). For both western and eastern central Asia, the mean specific humidity of air particles from western Asia was larger in NDJFMA than in MJJASO. Because of the obstruction of the Tibetan Plateau, few air particles from the Indian Ocean and Indian subcontinent can arrive at central Asia (as seen in Figs. 4 and 5).

b. Spatial patterns for the changes in moisture of the target air particles

The cluster mean trajectories of the target air particles could adequately show the moisture pathways but could not describe the corresponding strength. Thus, the moisture distributions associated with all the target air particles were examined in this section.

Figure 6 shows the spatial patterns for the mean water content of all the target air particles before reaching central Asia. The results for the backward-integrated 10 days are first discussed (left column of Fig. 6). For the precipitation in western central Asia, the large-water-content band expanded from northern Eurasia to western Asia, with the largest value over the eastern portion of the target region during MJJASO, the local dry season

FIG. 6. Time evolutions of the spatial patterns for the backward-integrated water content (kg m^{-2}) of all the target air particles before reaching central Asia. Results are from (a)–(d) WCA_MJJASO, (e)–(h) WCA_NDJFMA, (i)–(l) ECA_MJJASO, and (m)–(p) ECA_NDJFMA. Columns indicate the back-tracking integrals for (left to right) days 10–1, days 3–1, days 6–4, and days 10–7.

(larger than 200 kg m^{-2} ; Fig. 6a). During NDJFMA (the local wet season), however, the large band of atmospheric water content expanded from the middle of Eurasia to western Asia, with the highest value over the southwestern portion of the target region (larger than 150 kg m^{-2} ; Fig. 6e) in NDJFMA. The mean atmospheric water content over northern Eurasia during MJJASO was much larger than that during NDJFMA. The mean water content over the North Atlantic Ocean was around $15\text{--}50 \text{ kg m}^{-2}$ during both MJJASO and NDJFMA, much lower than that over Eurasia.

In eastern central Asia, a large center of water content was present in local regions, with a value of 200 kg m^{-2} during MJJASO (local wet season), which extended westward to Europe and southward to the Indian subcontinent with decreasing magnitude (Fig. 6i). However, during NDJFMA, this large center was located in the southern portion of eastern central Asia, extending southwestward to western Asia, which was different from the pattern during MJJASO (Fig. 6m). The atmospheric moisture content over eastern central Asia, northern Eurasia, western Eurasia, and the Indian subcontinent (western Asia) during MJJASO was larger

(lower) than that during NDJFMA. The atmospheric water content over western Asia was larger for western central Asia than that for eastern central Asia, demonstrating that moisture from western Asia may play a more important role in the precipitation over western central Asia. During both MJJASO and NDJFMA, the atmospheric water content over the North Atlantic Ocean was below 25 kg m^{-2} , much lower than that over Eurasia. These results suggest that moisture from the North Atlantic Ocean may barely affect the precipitation in central Asia.

The time evolutions of the spatial patterns for the backward-integrated atmospheric water content of all the target air particles are further examined (center and right columns of Fig. 6). For both western and eastern central Asia during MJJASO and NDJFMA, the magnitudes of the mean water content over the target regions and western Eurasia (the large center) were lower over more back-tracking days. The 10 back-tracking days were separated into the latest 3 days (days 3–1, from $t = -6 \text{ h}$ to $t = -72 \text{ h}$), the middle 3 days (days 6–4, from $t = -78 \text{ h}$ to $t = -144 \text{ h}$), and the earliest 4 days (days 10–7, from $t = -160 \text{ h}$ to $t = -240 \text{ h}$). The spatial

FIG. 7. Time evolutions of the spatial patterns for the backward-integrated evaporation minus precipitation (kg m^{-2}) of all the target air particles before reaching central Asia. The rows from top to bottom indicate the results from (a)–(d) WCA_MJJASO, (e)–(h) WCA_NDJFMA, (i)–(l) ECA_MJJASO, and (m)–(p) ECA_NDJFMA. Columns indicate the back-tracking integrals for (left to right) days 10–1, days 3–1, days 6–4, and days 10–7.

distributions of the atmospheric water content over days 3–1 were similar to the results over days 10–1, which demonstrates that the atmospheric water content when integrated for backward over 10 days mainly originated from the latest 3 days (Figs. 6b,f,j,n).

In western central Asia during MJJASO (NDJFMA), the water content over western Asia mainly originated from the days 6–4 (days 3–1), followed by days 10–7 (days 6–4) and days 3–1 (days 10–7). In eastern central Asia during NDJFMA, the water content over western Asia mainly originated from days 6–4, followed by days 10–7 and days 3–1. The water content over the North Atlantic Ocean mainly originated from days 10–7, followed by days 6–4 and days 3–1. This implies that the moisture from regions farthest away tended to have the longest transport time in arriving target regions.

The region at a given time would be dominated by one of the processes (i.e., evaporation or precipitation). The target air particles may have released (collected) moisture over the regions dominated by precipitation (evaporation) process en route to the target areas. Note that the net effect of evaporation minus precipitation was

identified by analyzing the changes in specific humidity. To examine the potential moisture regions, the integrals of evaporation minus precipitation ($e - p$) over days 10–1 for central Asia are shown in the left column of Fig. 7. During both MJJASO and NDJFMA, the locations of moisture source ($e - p > 0$) and moisture sink ($e - p < 0$) regions were nearly identical between eastern and western central Asia. For both western and eastern central Asia during MJJASO, the moisture source regions occurred in central Asia, western and northern Eurasia, and North Africa, while the sink regions occurred in most areas of the North Atlantic Ocean and North America (Figs. 7a,i). During NDJFMA, the moisture source regions for both western and eastern central Asia occurred in southern central Asia, southwestern Eurasia, western Asia, southern portion of the North Atlantic Ocean, and North Africa, while the moisture sink regions occurred in northern and western Eurasia and the northern portion of the North Atlantic Ocean.

The time evolutions of the spatial patterns for the backward-integrated ($e - p$) were also examined (center and right columns of Fig. 7). During both MJJASO and

FIG. 8. Spatial patterns for the total contributions (%) from the moisture source regions over 10 days to the precipitation over central Asia: (a) WCA_MJJASO, (b) ECA_MJJASO, (c) WCA_NDJFMA, and (d) ECA_NDJFMA.

NDJFMA, local regions were an important moisture source region for both western and eastern central Asia, contributing moisture to the target precipitation over all the back-tracking days. The northern and western regions of Eurasia, the important source regions for precipitation in both western and eastern central Asia during MJJASO, mainly contributed moisture over days 6–4 and 10–7, with a larger magnitude for the former. However, northern and western Eurasia acted as moisture sink regions over all 10 back-tracking days during NDJFMA for western and eastern central Asia.

During both MJJASO and NDJFMA, western Asia contributed more to the precipitation in western central Asia over all the back-tracking days and even partially contributed to the precipitation in eastern central Asia over days 6–4 and days 10–4. The Indian subcontinent was a moisture sink region for the precipitation in eastern central Asia during MJJASO over all the back-tracking days but a moisture source region for the precipitation in both western and eastern central Asia during NDJFMA over days 6–4 and 10–7. Moisture over North Africa mainly contributed to the precipitation in western central Asia during both MJJASO and NDJFMA but in eastern central Asia during NDJFMA, which occurred over days 10–7 and 6–4. For both western and eastern central Asia during MJJASO and NDJFMA, moisture was lost over

most of the North Atlantic Ocean, which mainly occurred in days 10–7, followed by days 6–4.

c. Quantified contributions from moisture source regions

The spatial patterns for the total contributions from source regions to the target precipitation events as derived from all the back-tracking trajectories were shown in Fig. 8. Note that the contributions were derived from the moisture source attribution method illustrated in section 2c. Over these 10 days, the moisture contribution associated with precipitation over western and eastern central Asia was 96.71% and 97.39% during MJJASO and 96.74% and 96.53% during NDJFMA, respectively. The remainder originated from moisture that existed 10 days prior. In terms of the land-cover types, the regions contributing to precipitation in central Asia were mainly barren or sparsely vegetated, grasslands, croplands, and open shrublands (Table 1). The water bodies (the North Atlantic Ocean, Black Sea, Caspian Sea, and Mediterranean Sea) mainly contributed moisture to the precipitation events during MJJASO and NDJFMA for western central Asia but during NDJFMA for eastern central Asia.

The spatial patterns of the moisture contributions for both western and eastern central Asia during both MJJASO and NDJFMA were similar to those of the

FIG. 9. Contributions (%) from the moisture source regions to the precipitation over central Asia. Note that the results are derived from all the target air particles. The red, brown, steel-blue, yellow, magenta, green, blue, gray, and wheat-colored bars indicate the total contributions from western and eastern central Asia, northern Eurasia, western Eurasia, the North Atlantic Ocean, North Africa, western Asia, the Indian subcontinent, and the sum of other regions over 10 back-tracking days, respectively. The black bars indicate the total contributions from atmospheric moisture that existed 10 days prior.

mean water content (left column of Fig. 6), showing larger contributions over regions closer to the target areas (Fig. 8). Thus, local regions and Eurasia were the most important moisture source regions for the precipitation in both western and eastern central Asia. Additionally, moisture from western Asia played an important role in the precipitation over western central Asia during both MJJASO and NDJFMA and over eastern central Asia during NDJFMA. Although many air particles originated from the North Atlantic Ocean, the corresponding contribution to the precipitation over central Asia was small because of the low mean water content and ongoing moisture release to the distant target regions.

The total contribution from these major regions (western and eastern central Asia, northern Eurasia, the North Atlantic Ocean, western Asia, and the Indian subcontinent, as seen in white boxes in Fig. 1) to the precipitation in central Asia was evaluated. During MJJASO and NDJFMA, the total contribution from these major regions (which is different from the aforementioned contribution of all the regions) was around 96.05% and 92.71% for western central Asia and 92.36% and 91.85% for eastern central Asia, respectively (Fig. 9 and Table 2).

In western central Asia, the moisture that was associated with precipitation during MJJASO mainly originated from local regions (49.11%), western Eurasia (21.47%), and western Asia (11.37%), as seen in Table 2 and Fig. 9. During NDJFMA, the important moisture source regions for western central Asia were local regions (33.92%), western Asia (27.50%), and western Eurasia (17.60%). In eastern central Asia, the moisture that was associated with precipitation mainly originated from local regions (52.38%), western central Asia (25.22%), and northern Eurasia (9.26%) during MJJASO. During NDJFMA, however, the moisture for eastern central Asia mainly originated from western central Asia (30.86%), local regions (30.82%), western Asia (10.31%), and western Eurasia (10.26%) during NDJFMA. The differences of moisture sources in precipitation events between the dry and wet seasons mainly occurred in western Asia and local regions for western central Asia, but in local regions only for eastern central Asia.

4. Summary

The ecosystem in the arid central Asia area is greatly affected by changes in precipitation. Revealing moisture

TABLE 1. Moisture source contributions (%) of different land cover types. ECA = eastern central Asia; WCA = western central Asia. The boldface rows indicate the major source regions in terms of the land-cover types.

Land cover	WCA_MJJASO	WCA_NDJFMA	ECA_MJJASO	ECA_NDJFMA
Water bodies	15.57	21.17	3.49	11.66
Evergreen needleleaf forest	2.23	0.83	1.93	0.89
Evergreen broadleaf forest	0.01	0.03	0.02	0.018
Deciduous needleleaf forest	0.07	0.00	0.65	0.09
Deciduous broadleaf forest	0.06	0.07	0.02	0.07
Mixed forest	2.87	1.28	4.90	1.29
Closed shrublands	0.01	0.02	0.01	0.02
Open shrublands	10.97	12.34	11.53	12.96
Woody savannas	0.08	0.08	0.40	0.15
Savannas	0.07	0.19	0.01	0.13
Grasslands	22.74	14.40	31.01	24.86
Permanent wetlands	0.11	0.01	0.24	0.02
Croplands	19.46	12.19	14.53	12.60
Urban and built-up	0.00	0.00	0.00	0.00
Cropland/natural vegetation mosaic	1.20	1.04	0.35	0.83
Permanent snow and ice	0.05	0.05	0.24	0.28
Barren or sparsely vegetated	21.18	33.00	28.04	30.66
Unclassified	0.01	0.01	0.00	0.01

TABLE 2. Moisture source contributions (%) of different subregions.

Subregion	WCA_MJJASO	WCA_NDJFMA	ECA_MJJASO	ECA_NDJFMA
WCA	49.11	33.92	25.22	30.86
ECA	1.32	0.63	52.38	30.82
N. Eurasia	7.60	2.91	9.26	3.09
W. Eurasia	21.47	17.60	3.70	10.26
N. Atlantic	2.68	4.86	0.57	3.92
N. Africa	1.73	4.23	0.11	2.02
W. Asia	11.37	27.50	0.68	10.31
Indian Sub.	0.77	1.06	0.44	0.57
Other regions	0.66	4.03	5.03	4.68
10 days ago	3.29	3.26	2.61	3.47

sources is a key step in understanding the physical mechanisms that are responsible for regional precipitation variations. In this study, the Lagrangian model FLEXPART was employed to address the moisture sources that are associated with precipitation in central Asia. The main results are as follows.

Multiple observational products of precipitation revealed an obvious annual precipitation cycle in central Asia. Remarkably, the times of the dry and wet seasons were the opposite for western and eastern central Asia, which are bounded by 75°E. In western (eastern) central Asia, the wet season occurred in NDJFMA (MJJASO) and the dry season occurred in MJJASO (NDJFMA). The observed annual precipitation cycle in central Asia was adequately captured by CFSR. Thus, the moisture sources that were associated with precipitation events in central Asia were identified in terms of the dry and wet seasons over both western and eastern central Asia.

For both western and eastern central Asia, the moisture contribution that was associated with precipitation during both MJJASO and NDJFMA was more than 96% over 10 back-tracking days. Local regions and Eurasia (mainly western Eurasia, northern Eurasia, and western Asia) were the most important moisture regions for the precipitation in central Asia. Western central Asia also greatly contributed to the precipitation in eastern central Asia. However, the contributions from those source regions varied with the season. For western central Asia, the moisture contributions from local regions, western Eurasia, northern Eurasia, and western Asia were 49.11%, 21.47%, 7.60%, and 11.37% during MJJASO and 33.92%, 17.60%, 2.91%, and 27.50% during NDJFMA, respectively. For eastern central Asia, the moisture contributions from local regions, western central Asia, western Eurasia, northern Eurasia, and western Asia were 52.38%, 25.22%, 3.70%, 9.26%, and 0.68% during MJJASO and 30.82%, 30.86%, 10.26%, 3.09%, and 10.31% during NDJFMA, respectively. Thus, the differences in moisture sources that were associated with

precipitation between the dry and wet seasons mainly occurred in local regions for eastern central Asia, but in local regions and western Asia for western central Asia.

The transport of moisture to target regions from source regions was greatly affected by atmospheric circulation. In association with the precipitation during both MJJASO and NDJFMA, a deep low trough occurred over the region to the west of target areas. Thus, moisture over Eurasia to the north and west of the target regions was mainly transported to central Asia by a westerly and southwesterly in association with a deep low trough. The moisture transport from western Asia was influenced by an anticyclone over North Africa to western Asia. This anticyclone occurred at both middle and lower troposphere, and its intensity varies in seasons. Because of the shorter distance of western Asia from western central Asia than from eastern central Asia, the moisture over western Asia was directly transported to western central Asia by a southwesterly to the northeast of the anticyclone, but indirectly transported to eastern central Asia by a westerly that was associated with the aforementioned deep low trough. Therefore, the moisture contribution from western Asia to the precipitation over western central Asia was larger than that over eastern central Asia.

This study addressed the moisture sources associated with precipitation in dry and wet seasons for both western and eastern central Asia based on the selected 90 daily extreme precipitation events, and the spatial patterns of selected events are similar to that of the mean precipitation (Fig. S5). These implied that the moisture sources for the selected events may be similar to that for the mean precipitation. As revealed in this study, because of far from the North Atlantic Ocean and the obstruction of the Tibetan Plateau, the moisture contributing to precipitation during both wet and dry seasons in central Asia was mainly from local regions and Eurasia. The mean moisture content of atmosphere over land was much lower than over ocean, and tends to

decrease in the regions with higher latitude and longer distance from ocean (Fig. S6). As a result, central Asia became a region characterized by the arid and semiarid climate.

The results for arid central Asia were similar to the results for the regions in northern and western East Asia, in which the moisture is also mainly from land moisture sources (Guo et al. 2019). In contrast, the precipitation in humid monsoon regions (such as the Indian subcontinent and southeastern East Asia) is dominated by the moisture from ocean regions while land moisture sources also have a great impact (Pathak et al. 2014, 2017; Guo et al. 2019). These implied that the regions located farther inland (or characterized by less precipitation amount) tend to be more largely impacted by the land moisture sources, as revealed in Guo et al. (2019).

Moisture studies focusing on monsoon Asia have addressed the moisture sources in terms from different time scales, and investigated the influence of Asian monsoon and variation in tropical sea surface temperature (Pathak et al. 2014, 2017; Guo et al. 2019). This study mainly revealed the moisture sources associated with precipitation in central Asia as well as the seasonal variations. The variations of moisture sources associated with precipitation at subseasonal to interannual time scales have not been revealed. The precipitation variations in central Asia are largely influenced by the changes in westerlies (Chen et al. 2011; Zhao et al. 2014; Peng and Zhou 2017). Thus, for the future, the variations in moisture sources as well as the influence of westerlies at different time scales should be investigated in detail.

The precipitation in central Asia was largely influenced by the topography effect. On the one hand, the forced updrafts associated with complex topography (such as the high mountains in the southern central Asia) can favor the precipitation events. On the other hand, the moisture originated from the ocean (mainly the Indian Ocean) to the south of central Asia can be obstructed by the Tibetan Plateau, resulting in few air particles from the Indian subcontinent and Indian Ocean reaching central Asia (as seen in Figs. 3 and 4). To determine the influence of topography on the precipitation in central Asia more clearly, corresponding numerical simulations would be conducted for the future study. Although the timing of dry and wet seasons for western and eastern central Asia were opposite (Fig. 2), the atmospheric moisture content associated with both selected precipitation events (Fig. 6) and mean precipitation (Fig. S6) over Eurasia is larger in MJJASO than in NDJFMA. These results implied that the precipitation efficiency may vary by season for western and eastern central Asia and also need to be addressed in detail in a future study.

The moisture source detection method used in this study was conducted by analyzing the changes in specific humidity along moving trajectories. Only the air particles that were precipitating at the starting time were traced backward in time to identify the moisture sources. Thus, the numbers of target air particles at release times were determined by whether or not precipitation occurs. Besides, as only one of the processes (the changes in specific humidity represent a net effect of evaporation minus precipitation) can be considered at a time, the contributions of evaporation and precipitation cannot be well separated (Sodemann et al. 2008; Gimeno et al. 2012). This may be fixed to some extent by analyzing based on the outputs with higher frequency (i.e., the releasing times) and finer spatial scale (Sodemann et al. 2008; Gimeno et al. 2012). Precipitation events that occurred at earlier time (e.g., consecutive precipitation days, as seen in Fig. S3) may also contribute to the present precipitation events, resulting in an overestimation of the local moisture contributions estimated by using this method. To reduce the uncertainties resulting from single methodology, the moisture contributions associated with precipitation in central Asia should be investigated for further study by employing different methods, such as an Eulerian framework (Gimeno et al. 2012; Guo et al. 2019) and the Dynamic Recycle Model (Hua et al. 2017; Pathak et al. 2017).

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