Moisture sources of extreme summer precipitation events in North Xinjiang and their relationship with atmospheric circulation

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Abstract

In this study, the daily observational precipitation data and NCEP reanalysis data during 1951–2014, Euler and Lagrangian method were used to investigate the moisture sources of summer extreme precipitation events in North Xinjiang. The results show that water vapor at low and upper levels of most summer heavy rain (more than 50 mm d⁻¹ and less than 100 mm d⁻¹) in North Xinjiang are mainly transported by westerly circulation from the North Atlantic Ocean and the Eurasian continent. However, rainstorms of more than 100 mm d⁻¹, which are rarely observed, are dominated by vertically integrated moisture from the North Atlantic, Arctic Oceans, and the Eurasian continent, in addition to low-level moisture from the Indian Ocean. Among these sources, the anomalous low-level moisture from the Indian Ocean, which is closely associated with stronger meridional circulation, is considered to be more important with respect to rainstorms. On the days prior to rainstorm days, stronger meridional circulation leads to an anomalous pressure gradient force, which can transport low-level moisture from the Indian Ocean along the eastern periphery of the Tibetan Plateau to North Xinjiang. Furthermore, moisture from the North Atlantic, Arctic Oceans, the Eurasian continent, and the Indian Ocean converge together to influence rainstorm development in this region.

Keywords: North Xinjiang; Moisture sources; Extreme precipitation events; Lagrangian trajectory model; Indian Ocean

1. Introduction

North Xinjiang (NX) is located in the western part of northwestern China, where precipitation is scarce. This region is far from ocean, and the movement of water vapor is blocked by the Tibetan Plateau and Tien Shan Mountains (Fig. 1, Feng and Fu, 2013). In recent years, global warming has impacted the water cycle over land and has led to regional moisture variations. Many studies have been conducted to better understand the moisture variations in Xinjiang and the nearby arid area. In this respect, researchers have determined that certain indicators—annual precipitation and soil moisture levels—relate to moisture conditions, as these have been increasing over recent decades in the inland lake area of Xinjiang and the nearby arid area (Jiang et al., 2005; Feng et al., 2007; Su and Wang, 2007; Chen et al., 2011). Evidence suggests that, since the mid-1980s, the climate and environment of Xinjiang have been undergoing a shift from a warm-dry to a warm-wet regime (Shi et al., 2007). Both the intensity and path of water vapor transport play important roles in regional moisture variations, so it is important to analyze the moisture sources of precipitation to gain an understanding of Xinjiang's warm wet regime in the context of global warming.
Previous studies have suggested that the climatological water vapor influencing Xinjiang and the nearby arid area primarily originates from the west (Yatagai, 2003; Huang et al., 2013). Huang et al. (2015) analyzed summer precipitation and its association with moisture and atmospheric circulation within the Tarim Basin and found that variations in anomalous summer precipitation have been dominated by water vapor originating from the south and east, and that anomalous water vapor fluxes are closely related with the circum global teleconnection (CGT) and the meridional teleconnection pattern around 50°–80°E. However, the moisture sources of precipitation in NX have not been understood clearly.

Additionally, most studies on water vapor transport have focused on climatological rather than precipitation events, and to date no attempts have been made to understand the moisture sources of extreme precipitation events with differing intensities in NX. Globally, the frequency and intensity of extreme precipitation events have shown noticeable increasing trends in relation to global warming (Easterling et al., 2000a, 2000b; Goswami et al., 2006). As NX is located in both arid and semiarid regions, only a relatively few days of precipitation are required to contribute most of the typical summer precipitation. The total annual precipitation in this region is less than 400 mm, with most occurring during summer. As such, extreme precipitation events in this region cause enormous variations in summer precipitation levels. Yang (2003) argues that in the 1980s the climate in Xinjiang shifted from a warm-dry to a warm-wet regime, based on the increased frequency of extreme precipitation events. The focus of this study, therefore, is to analyze the moisture sources of summer extreme precipitation events in NX.

2. Data and methods

The daily precipitation data from the China Ground Daily Climate Dataset Version 3.0 (obtained from 824 national meteorological stations) was used to analyze extreme precipitation events. This dataset covers the period from January 1, 1951 to December 12, 2014, and its quality and uniformity are maintained by the National Meteorological Information Center. Precipitation at 29 stations falls mainly during the summer time (June–August) in NX were used. In this respect, the analysis focuses on water vapor transport during 1951–2014 for two precipitation scenarios: 1) heavy rain days as Case 1 (daily precipitation more than 50 mm d\(^{-1}\) and less than 100 mm d\(^{-1}\), \(n = 45\) d), and 2) rainstorm days as Case 2 (daily precipitation more than 100 mm d\(^{-1}\), \(n = 2\) d). In addition, daily and monthly geopotential height, winds, vertical velocity, and specific humidity at various pressure levels for 1951–2014 were obtained from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996).

To evaluate the impacts of water vapor transport on precipitation in NX, the vertically integrated horizontal water vapor fluxes were calculated by the following equation:

\[
\overset{\text{Q}}{\nabla} = \frac{1}{g} \int_{300\text{hPa}}^{P_H} q \nabla dP
\]
where \( q, g, P_s, \overline{V} \) and \( \overline{Q} \) represent the specific humidity, gravity, surface pressure, horizontal velocity, and water vapor flux, respectively. When computing water vapor fluxes, we omitted pressure levels below surface pressure that are due to the topography. To evaluate the relative roles of the low and upper water vapor levels on NX precipitation, the water vapor fluxes were calculated at low levels (1000–700 hPa) and upper levels (700–300 hPa).

Additionally, the Lagrangian trajectory method was employed to confirm the water vapor transportation. Water vapor tracks were computed using the HYSPLIT Lagrangian trajectory model developed at the National Oceanic and Atmospheric Administration (NOAA) (Draxler and Hess, 1997).

To determine these water vapor tracks, the 6-hourly mean NCAR/NCEP reanalysis data was used (Kalnay et al., 1996) as model inputs. Using these data, the HYSPLIT model yielded backward tracks for the preceding 10 days, which we combined into one water vapor track.

3. Water vapor origin

3.1. Climatology water vapor origin

Prior to analyzing the water vapor transportation of extreme precipitation events in NX, we determined the water vapor fluxes of the vertically integrated summer climatology. The water vapor fluxes from the west (North Atlantic) prevail in Central Asia and then turn eastward together with fluxes from the northwest (Arctic Ocean), which then arrive at the study region. This structure indicates a weak ridge north of the Caspian and Aral Seas, and a weak trough over northwestern NX (Fig. 1). Compared to the Asian monsoon region, there are only slight water vapor fluxes affecting NX. Due to the westerlies, the majority of the water vapor transported to the study region comes from the west and northwest and leaves the region from the east. Additionally, the Tibetan Plateau and Tienshan Mountains, located in the south of the study area, block the mean water vapor fluxes transported to this region from extending south. These climatology results are similar to those of previous studies (Yatagai and Yasunari, 1998; Yatagai, 2003).

3.2. Water vapor origin for extreme precipitation events

As previously stated, precipitation in NX falls mainly during summer (June–August), therefore here we focus only on extreme summer precipitation events in this region. We analyzed water vapor transport to NX for the different precipitation scenarios defined in Section 2. Fig. 2 shows the composite water vapor fluxes and atmospheric circulation on the day prior to heavy rain (PHR) day and on heavy rain (HR) day, respectively. As shown in Fig. 2, the composite atmospheric circulation pattern has a similar pattern on both types: there is a ridge north of the Caspian and Aral Seas. In addition, there is a trough along the northwestern China border and another ridge over north-central China, downstream of the trough. Due to these similar atmospheric circulation patterns, the transportation of water vapor is nearly the same on PHR and HR days. Apart from the moisture from ocean areas, previous studies have documented water vapor from the Eurasian continent as being important sources of precipitation over Eurasia (Numaguti, 1999), and especially for precipitation in inland China (Sun and Wang, 2014). Also, since the Eurasian continent is located downwind of the North Atlantic Ocean, on PHR days, low- and upper-level water vapor is transported from the North Atlantic Ocean and the Eurasian continent to Central Asia by the westerlies (Fig. 2a and b), and then is further transported to NX on HR days (Fig. 2c and d).

Fig. 3 shows the composite atmospheric circulation and water vapor fluxes for the day prior to rainstorm (PRS) day and on rainstorm (RS) day, respectively. On PRS days, the ridge over northern China is stronger, which may enable the low-level water vapor fluxes along the eastern periphery of the Tibetan Plateau to bend westward and facilitate transport to NX (Fig. 3a). Compared with HR days, the ridge north of the Caspian and Aral Seas is very noticeable, and the trough north of NX is deeper and penetrates over northern India on PRS days. The trough also brings an amount of water vapor from the north to the study region (Fig. 3). Furthermore, on RS days, the two low-level moisture fluxes converge in NX, which is conducive to the development of precipitation.

To summarize, water vapor transport to NX has two main origins on HR days: vertically integrated water vapor from the North Atlantic Ocean and the Eurasian continent transported to NX by westerlies. However, on RS days, the meridional water vapor transport to NX is stronger, and we have identified four main sources. Vertically integrated water vapor from the North Atlantic, Arctic Oceans, and the Eurasian continent converge in Siberia and together are transported to NX. The fourth and remarkable source is the low-level water vapor fluxes that move from the northern Indian Ocean along the eastern periphery of the Tibetan Plateau and then bend westward to NX on PRS days. Low-level water vapor transportation from the northern Indian Ocean has become increasingly important on RS days. These results are similar to those determined in Huang et al. (2015), that southerly water vapor fluxes can be transported to the south of the Tibetan Plateau, and along the eastern periphery of the plateau at a low-level, to affect summer precipitation in the Tarim Basin. The difference is that the southerly water vapor fluxes affect summer precipitation in the Tarim Basin on RS days, while the southerly water vapor fluxes affect NX on PRS days.

3.3. Water vapor origin based on the Lagrangian trajectory model

The Lagrangian trajectory model was used to confirm the transportation of water vapor. We selected all precipitation events occurring during summer seasons from 1951 to 2014, and we tracked their backward trajectories for 240 h at different levels. The results suggest that the water vapor predominantly affecting NX precipitation originates from two regions: the North Atlantic and the Arctic Oceans (Fig. 4). In addition, some low-level water vapor appears to pass over the
eastern Tibetan Plateau and travel to NX, which originates from the Indian Ocean (Li et al., 2012, 2016) and is transported to NX via a unique atmospheric circulation pattern (Fig. 3a). Therefore, in addition to the North Atlantic and Arctic Oceans, water vapor transport from the Indian Ocean has become increasingly important in NX on RS days.

Next, we computed and examined the frequency of precipitation events by dividing the top 50 daily summer precipitation events in 1° x 1° grid boxes by the total number of summer precipitation events in NX. We conducted analyses for all summer precipitation events and for the top 50 daily summer precipitation events. Fig. 5a and d show that, climatologically,
Fig. 4. Water vapor tracks of all precipitation events at (a) 2 km above ground level, and (b) 3 km above ground level. Black dots indicate end-point position.

Fig. 5. Passage frequencies of precipitation events in each 1° × 1° latitude–longitude grid box for, (a) climatology of all precipitation events, (b) top 50 daily precipitation events in NX, and (c) anomalies at 2 km above ground level and in summer during 1951–2014; (d) As in (a), (e) as in (b), (f) as in (c) but at 3 km above ground level.
water vapor frequently passes from the west at a high density over NX, where the tracks then usually end. For the top 50 daily summer precipitation events (Fig. 5b and e), however, the frequency of water vapor passage significantly differs from the climatology: it increases from the east and south of NX, and can be clearly observed to be anomalous (Fig. 5c and f).

4. Conclusions and future prospects

In this study, we analyzed the moisture sources of summer extreme precipitation events in North Xinjiang, northwestern China, and their association with atmospheric circulation. The results suggest that the atmospheric circulation pattern and water vapor transportation for summer heavy rain days (more than 50 mm d\(^{-1}\) and less than 100 mm d\(^{-1}\)) are similar to the known climatological pattern. The vertically integrated water vapor fluxes during heavy rain days in summer over NX come from the North Atlantic Ocean and the Eurasian continent, which are transported by westerlies. However, the meridional circulation is stronger on rainstorm days (more than 100 mm d\(^{-1}\)), and the water vapor originates from four sources: the North Atlantic, Arctic Oceans, the Eurasian continent, and the Indian Ocean. These sea and land bodies are also the origins of some of the moisture over NX, which originates from multiple sources and has a complex vertical structure. Due to the stronger meridional circulation of rainstorm days, low-level water vapor fluxes from the Indian Ocean are transported along the eastern periphery of the Tibetan Plateau, where they bend westward to NX. This moisture originates from the Indian Ocean and is the most important factor leading to rainstorms in NX.

The Lagrangian trajectory model was also used to confirm these water vapor transportation results, which are similar to those determined by the Euler method. Furthermore, the passage frequency of precipitation events shows that more moisture is transported from the east and south when extreme precipitation events occur.

Understanding the moisture sources of summer extreme precipitation events in NX is very important for the management of the regional ecosystem and environment. However, we note that the increased frequency of extreme precipitation events contributing to the climate in Xinjiang has shifted from that of a warm-dry to a warm-wet regime only during recent decades. The further development of global warming is causing some extreme weather/climate events to occur more frequently. Will the climate in this region become drier or wetter in the future? Are the moisture sources of past extreme precipitation events consistent with those of today? These scientific research issues must be further investigated.

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References


