# Water-vapor source shift of Xinjiang region during the recent twenty years*

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**Abstract** The aim of this paper is to investigate the climate water-vapor sources of Xinjiang region and their shifts during the past 20 years. First, the principle and steps are roughly regulated to seek the water-vapor sources. Second, the climate stationary water-vapor transport in troposphere is calculated to distinguish where the water vapor comes from by ERA-40 reanalysis. In addition, the collocation between the transport and the atmospheric column water vapor content is analyzed. The results show that the major vapor comes from the west side of Xinjiang for mid-month of seasons, apart from July while the water vapor comes from the north or northwest direction. The water vapor sources are different for different seasons, for example, the Caspian Sea and Mediterranean are the sources in January and April, the North Atlantic and the Arctic sea in July, and the Black Sea and Caspian Sea in October, respectively. In recent ten years more water vapor above Xinjiang comes from the high latitudes and the Arctic sea with global warming, and less from Mediterranean in comparison with the case of 1973—1986. In fact, the air over subtropics becomes dry and the anomalous water vapor transport direction turns to west or southwest during 1987—2000. By contrast, the air over middle and high latitudes is warmer and wetter than 14 years ago.

**Keywords: global warming, water-vapor source, water-vapor transport, precipitable water, Xinjiang climate, inter-decadal change.**

The climate of the past 20 years in China is characterized by monsoon decaying and interdecadal change of general circulation of atmosphere at the late 1970s under the background of global warming[1—3]. A notable event of the warming is the "north greening" in boreal summer according to satellite remote sensing, which led to an increase of the net primary production (NPP)[4]. This is probably due to the rapid warming that makes a prolonging of the growth period at high latitudes. Meanwhile, a more rainfall trend has been found in Xinjiang, an autonomous region in northwestern China, since the mid-1980s[5]. The rainfall is almost the only compensation to local water resources in such a semi-arid and extremely arid region, which is situated in the centre of Eurasian continent, far away from the oceans. An early estimate shows that $2.4\times10^{12}$t precipitation falling onto the area of Xinjiang per year, which is about 24% of the total water vapor that pass through the sky of Xinjiang from meteorological and hydrological observations and investigation collections in the late 1950s[6]. The water resources may fluctuate with climate variation, for instance, the mountain glacial is likely to shrink with global warming accompanying runoff and surface evapotranspiration increase, and lake expansion[7—10]. The climate wet tendency in Xinjiang has made a remarkable contrast with the severe drought in North China during the past 20 years[11,12]. Some research work has shown that the climate change signal in northwestern China may imply a regional climate transition from a warm-dry to warm-wet pattern[13,14]. The questions are what physical factors drive the climate transition in northwestern China and whether it is correlated to global warming or interdecadal change of general circulation of atmosphere. The specific mechanism may involve several aspects such as transient eddies, stationary waves, the water vapor transport (WVT), and the shifts of the water vapor sources (WVS). The following content of this paper will focus on the stationary WVT and WVS shifts during the past 20 years.

## 1 Precipitation

The monthly precipitation sequence of Xinjiang is made by the records of 12 meteorological stations,

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** To whom correspondence should be addressed. E-mail: daixg@tea.ac.cn namely, Kuche, Kashi, Hotian, Qieme, Nuoqiang, Urumqi, Yili, Tacheng, Altai, Wusu, Turpan, and Hami, located within Xijiang region among the 160 standard stations issued by China National Climate Centre (NCC). Xinjiang is such an area that the summer monsoon merely touched. Its seasonal precipitation distribution during 1951—2000 exhibits double peaks that appeared in July and October, respectively, with a minimum valley in September between them. The period May—July is the rainy season in Xinjiang. These characteristics are very different from the North China whose rainy period is embedded in its monsoon season with a single-peak rainfall distribution. There exist clear interdecadal changes in the annual precipitation sequence, with less rainfall from the mid-1960s to the late 1970s, and more rainfall from the 1950s to the beginning of the 1960s and since the mid-1980s (Fig. 1). Further study reveals that a similar pattern also exists in summer and winter rainfall sequences, respectively.

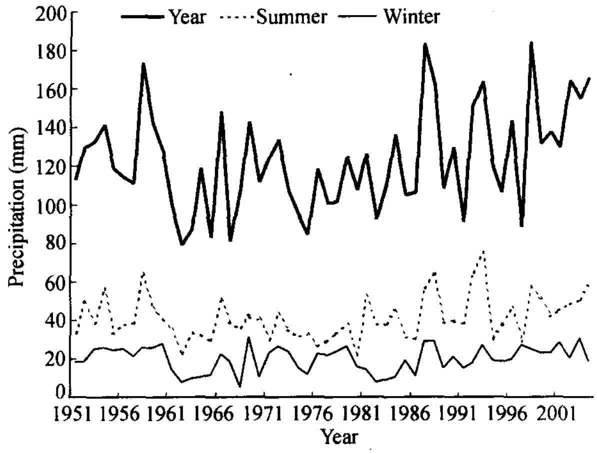

Fig. 1. Annual precipitation evolution of Xinjiang during 1951—2004.

The monthly precipitation also clearly shows an interdecadal change in 1986/1987 with a time scale of 14 years, in which the rainfall increments in July and January reach 74% and 49% of the rainfall anomaly percentage, respectively (Table 1).

Table 1. Precipitation anomaly percentage during 1987—2000 versus 1973—1986 (%)

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 49 | -3 | 22 | 10 | 28 | 4 | 74 | 56 | -8 | 25 | 19 | 46 |

Yamamoto et al.[16] confirmed a common jump point in 1987 for both January and July rainfall sequences with the running mean scale of 14—18 years, while they are in 1979 or 1980 with regard to the scale of 20 yeas. However, these jump points have not passed the significance test level of 0.05. Therefore, they are only regarded as the transition point rather than the abrupt change point for the monthly precipitation evolution considered.

## 2 Definition of water vapor source

Accurately defining a water source for a specific region is still an open question. The main difficulty is the existence of direct and indirect WVS during hydrological cycles between the earth surface and atmosphere. However, a water source, in general sense, may be regarded as the large lakes, seas or oceans in the climate upstream of the region, for instance, the Mediterranean, Caspian Sea and Black Sea are situated in the climate wind upstream of Xinjiang, and the water vapor evaporated from them can be transported to Xinjiang region. Thus, they might become the water sources of the region.

Generally, the water-vapor transport (WVT) can be decomposed into three parts, which attribute to the general meridianal cells, stationary waves and transient eddies. The first part is not important for mid- and high-latitude zones, while the transient eddy transport is often less than the stationary eddy part[17] in northern China. Actually, it is improper to define the WVS by means of transient eddy transport only because its norm and direction depend on not only the departures of specific humidity or wind, but also the correlation of them. Moreover, the actual transient moisture transport is usually orthogonal to climate wind flow, with a direction northward in mid- and high-latitudes[18]. Besides, the WVS may be different for different synoptic processes that bring rainfall to Xinjiang because of the different routes of water vapor transport to Xinjiang region for every process. With regard to the stationary WVT, its norm is proportional to both climate mean wind and specific humidity, and its direction is the same as the climate mean wind. Thus, the stationary WVT is the one that can be used to seek the climate WVS for a specific region.

Besides, whether a water surface can be regarded as a WVS also relies on the air thermal state above it.

If the water vapor evaporated from a water surface can be easily transported up to the mid-troposphere, the column water vapor content over the surface would be usually a regional maximal centre. Hence, the water surface is one of the vapor sources of atmosphere, and *vice versa*. The column water vapor content is also called precipitable water (PW), which is often measured by the depth (mm) or mass (kg or g) of the rainfall condensed by the total vapor in an air column.

Owing to the analysis above, the WVS of Xinjiang can be found by a retrospection method defined with the following five steps:

Step 1: Calculate a cumulated climate stationary WVT from surface to 300 hPa.

Step 2: Contour the streamline field using the WVT vector.

Step 3: Select the streamlines that cross the sky above the region considered, and find out the large lakes or seas under the streamlines from its upstream.

Step 4: Remove the water surfaces above which they do not reach PW maxima.

Step 5: Select the remained water surfaces close to the region as the WVS.

## 3 Water-vapor sources of Xinjiang

The climate WVS of Xinjiang can be identified from the stationary WVT and PW field by the following five steps mentioned above. This paper only considers the cases of typical seasonal months: January, April, July, and October. Firstly, as described in Step 1, the 1980—2000 stationary WVT fields of the troposphere for the four months are calculated respectively with ECMWF ERA-40 reanalysis[19] in a resolution of 2.5°×2.5° by the method of Simmonds et al.[17]. And secondly, a contour to the WVT and PW on a same sheet is made to do analysis (Fig.2).

There is a large PW minimum area over Xinjiang region in April, while several maximum areas exist over the southern Europe, including Mediterranean, Black Sea and Caspian Sea (Fig. 2(a)). The PW gradient orients northeast, i.e. from southern Europe to west Siberia. The WVT over Xinjiang is approximately along a direction from the west to the east of the region. From the retrospection method in Steps 3—5, it immediately turns out that the Mediterranean and Caspian Sea are the April WVS of Xinjiang region.

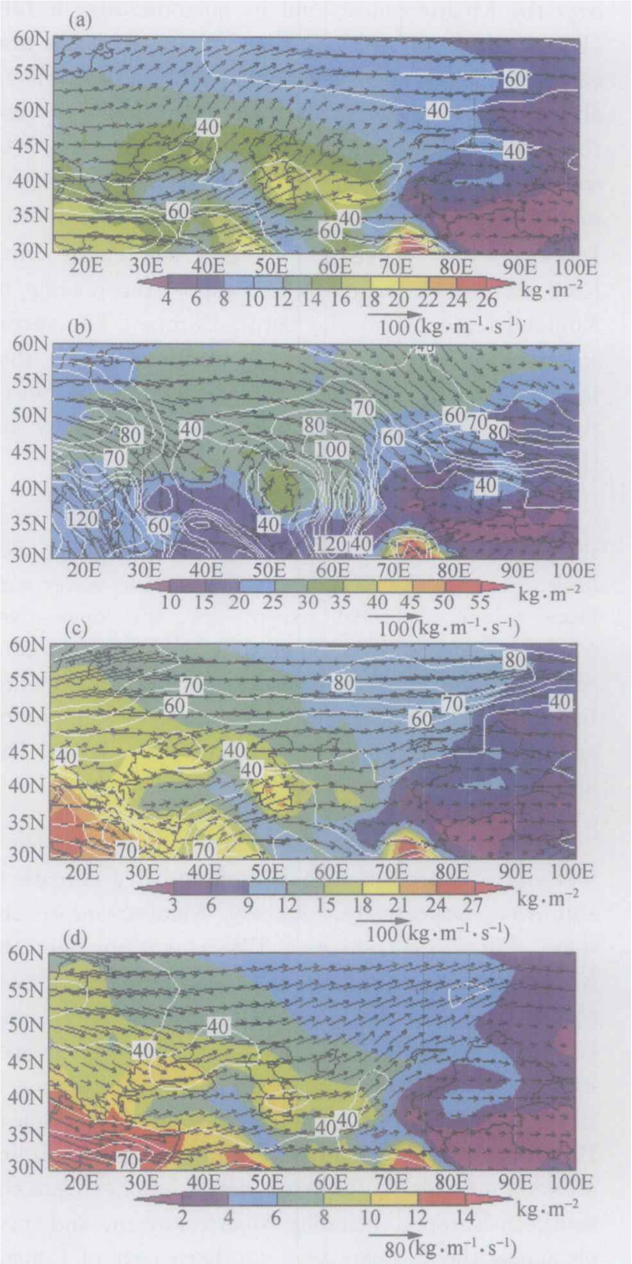

Fig. 2. Climate mean precipitable water and stationary water-vapor transport fields during 1980—2000 integrated from surface to 300 hPa. (a) April; (b) July; (c) October; (d) January. The white line in the panels describes the WVT norms.

As mentioned above, July is the mostly rainy month in Xinjiang, in which both PW and WVT reach their maximum, for example, the maximal WVT is even higher than 100 $kg \cdot m^{-1} \cdot s^{-1}$. The main PW maxima appears over a large area at mid- and high-latitudes, whereas the air above Mediterranean becomes dry, probably due to the control of subtropical high with descending air which restrains the evaporation and water vapor transportation to mid-troposphere. This leads to a relatively small PW over the Mediterranean and its surroundings in July (Fig. 2 (b)). The Black Sea and Caspian Sea also cannot be regarded as the water sources of Xinjiang although there are PW maxima over them, because the WVT vectors have southward components over southern Europe on one hand, and a very intensive meridianal WVT jet southward (with a maximum of 160 $kg \cdot m^{-1} s^{-1}$) exists in Central Asia on the other hand, which blocks the water vapor transporting to Xinjiang region from the South Europe. The retrospection to the water-vapor streamlines shows that the water vapor over Xinjiang comes from the North Atlantic and boreal Arctic sea. Therefore, they are the July water vapor sources of Xinjiang region.

For October, several PW maximal areas cover the Mediterranean, Black Sea, and Caspian Sea (Fig.2 (c)). The WVT vectors over the water surfaces orient eastward except for the ones over Mediterranean with southward components. In consequence, the Black Sea and Caspian Sea are identified as the October water-vapor sources of Xinjiang by applying the retrospection method in the climate PW and WVT fields for the month.

As is well known, the Mediterranean area has a wet and warm climate in winter and dry climate in summer, respectively, namely Mediterranean climate. Fig. 2 (d) shows a PW maximum over the Mediterranean in January. The Mediterranean is usually such an area where eddies act intensively in wintertime, which effectively transports the water vapor evaporated into the atmosphere. Hence, there is a PW maximum over the Mediterranean, in addition to Black Sea and Caspian Sea. The WVT streamline shows a maximal WVT band that originates from the southern Europe, including Mediterranean, and travels across the Caspian Sea, southern part of Central Asia, and then goes along the western edge of China border and finally arrives at the west Siberia, in which a split branch of the conveyor band turns eastward into the northern basin of Xinjiang. Thus, the Caspian Sea and the Mediterranean are the January water-vapor sources of Xinjiang.

For confirmation of our results, the NCEP reanalysis II[20] is also employed to search the water-vapor sources of Xinjiang. As expected, the investigation shows a very similar result to that made with ERA-40 in this paper.

## 4 Interdecadal change

The climate water-vapor sources might shift with climate change on the interdecadal time scale. The rainfall evolution has showed the interdecadal change occurred in 1986/1987, especially for the January and July sequences. Hence, the following investigation on the WVS shift will focus on the cases for the two months. The shift since 1987 can be revealed by comparing the WVT difference during 1987—2000 and 1973—1986 (Fig.3). Note that the departures of the WVT are usually much smaller than their norms and that the analysis should take the climate mean WVT field into account as a reference field (Fig.2) to find the direction of the anomalous water vapor transport in the recent 14 years.

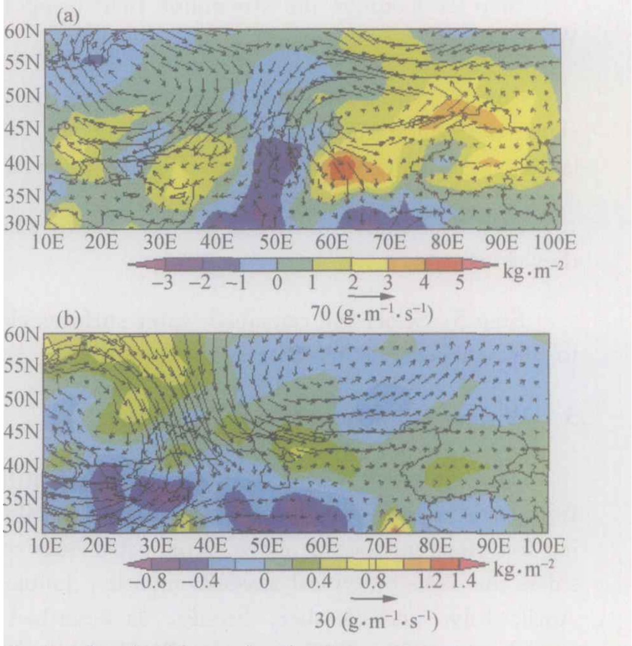

Fig. 3. Interdecadal anomalies of stationary water vapor transport integrated from surface to 300 hPa during 1987—2000 versus 1973—1986 using ERA-40 reanalysis. (a) July; (b) January.

Fig. 3 (a) shows several PW maximal centers over Xinjiang and a par of Central Asia for July case. There exists a clear conveyor band for anomalous WVT from Central Asia to the northern basin of Xinjiang, while another anomalous WVT jet is situated in Tarim basin, south of Xinjiang, which transports water vapor into the basin from the east side of Xinjiang, i.e. from its eastern adjacent provinces such as Qinghai and Gansu provinces. Such an interdecadal change of the stationary water-vapor transport can promote the humidity over Xinjiang and strengthen the local thermal convection and synoptic rainfall. If enlarge the area considered, we can find that the water vapor that comes from Central Asia is actually transported from remote northern Europe or Arctic Sea (Fig. 2(b)).

As for January, a long conveyor band of the anomalous WVT is linked from the northwest Europe throughout Caspian Sea and then the Xinjiang region accompanying a maximal belt of the positive PW anomalies for January case (Fig. 3 (b)). Since the two maximal belts are overlapped each other along the climate WVT streamlines (Fig. 2 (d)) and finally enter the Xinjiang region, it virtually enhances the water vapor transportation from northwestern Europe to Xinjiang in the winter month. On the other hand, the anomalous WVT vectors around Mediterranean are of westward or southward components in cope with the negative anomalies of the PW. This implies that the atmospheric column above Mediterranean has become drier than that in the previous 14 years, and the WVT from Mediterranean to Xinjiang has been reduced for January case since 1987, while more water vapor has come from mid- and high-latitudes. Obviously, the change in WVT field is greatly favorable to winter precipitation in Xinjiang during the recent 14 years.

As the average period extends to 21 years, the interdecadal PW change shows that more positive departure areas appeared at high latitudes than the ones made by an average scale of 14 years, whereas the areas with negative departures expand too around Mediterranean or over the subtropical zone. The calculation of the WVT interdecadal changes illustrates that more water vapor comes from the high latitudes east to the Ural mountain for July case, while from northern Europe for January case, in which the anomalous WVT pattern is similar to that in Fig. 3 (b), in addition to a maximal area appearing in Central Asia. Similarly, there is less PW above the Mediterranean zone, and less water vapor comes from Mediterranean to Xinjiang in the recent 20 years (1980—2001) in comparison with the period 1959—1978.

## 5 Observation examination

### 5.1 Surface vapor pressure

The PW augment in mid- and high-latitudes during 1987—2000 is an important implication for climate change and still needs to be confirmed by the observation, because of many satellite data introduced into the reanalysis data since 1980, which is a kind of non-homogeneity that might cause a false interdecadal change in the data. CRU TS2.0 is an analysis grid data set with a resolution of 0.5°×0.5°, which is derived directly from the surface observations through a simple interpolation method in Tyndall Centre, University of East Anglia, United Kingdom. A surface vapor pressure (hereafter denoted by $e$ or SVP) is available rather than PW or column water vapor content in the data set. Fortunately, the PW can be well estimated by the SVP due to their significant correlation (correlation coefficient: 0.93 on average)[21,22]. There is a linear relationship between them, expressed as $PW = 1.74e$, proved by a statistical regression analysis[22], by which the PW and its change can be estimated quantitatively by the SVP.

The interdecadal change of the SVP calculated during 1987—2000 versus 1973—1986 approximately confirms the distribution of the reanalysis PW anomalies in mid- and high-latitudes (Fig. 4). For example, there are a number of positive centers for the SVP departures around Xinjiang (Fig. 4 (a)), and a large area with positive SVP departures in high latitudes, and several patches of negative SVP departures in the south part of Central Asia, northwest Europe and Caspian Sea in July, coinciding well with the PW departures in Fig. 3(a), except for the east part of the Mediterranean, where almost all the area in Fig. 4 (b) is occupied by the positive SVP departures in January, in which several positive extreme centers in northwest Europe, Caspian Sea, Salty Sea, Central Asia and Xinjiang region are all corresponding to the ones in Fig. 3(b). The negative PW departure area is generally larger than the SVP areas, such as the high latitudes within 50°E—100°E and the zone along Mediterranean although several negative extremes of the PW departures are almost corresponding to the ones of the SVP departures.

### 5.2 Trend and interdecadal change

The SVP augment over a very large area may be related to global warming. Theoretically, vapor or humidity is much more sensitive to the warming than temperature because the saturation vapor pressure is a power function of temperature in terms of Magnus formula. The departures in Fig. 4 (a), (b) contain the trend term implicitly. To distinguish their contributions to the SVP change, the trend should be removed from the SVP sequence on every grid before calculating the interdecadal change.

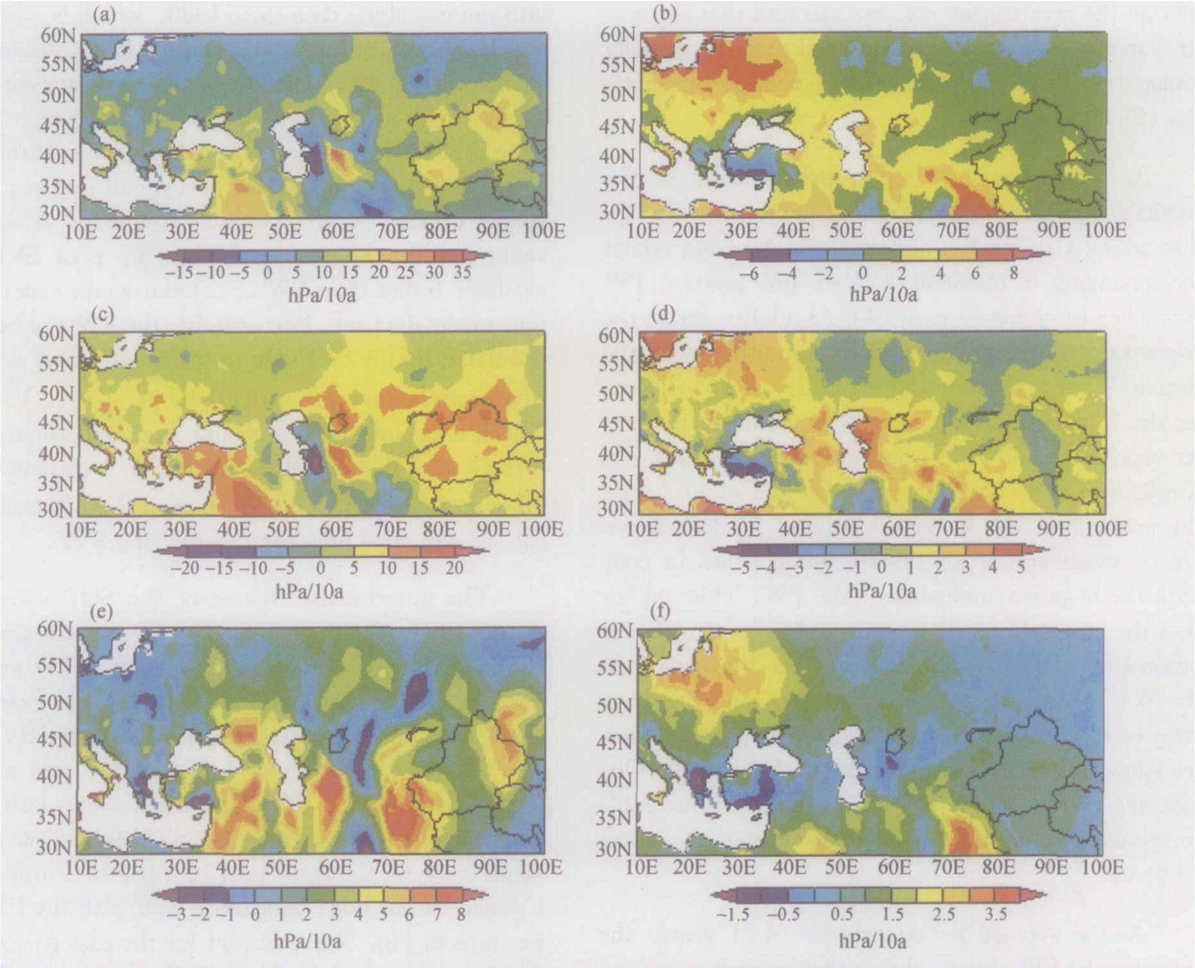

Fig. 4. Interdecadal changes of surface vapor pressures in January and July during 1987—2000 versus 1973—1986, and the trend for 1958—2000, estimated by CRU TS2.0. (a), (b) interdecadal change; (c), (d) pure interdecadal changes without trend; (e), (f) surface vapor pressure trends (hPa).

For July case the pattern of pure interdecadal change (PIC) of the SVP is similar to that in Fig. 4 (a), and the positive departures cover almost all the area showed in Fig. 4 (c), in which several maximal centers around Xinjiang, Salty Sea, Caspian Sea and the area east to Mediterranean are all corresponding to the ones in Fig. 4 (a). Besides, the trend distribution in Fig. 4 (e) exhibits a similar pattern to Fig. 4 (a), and most of the centers with positive trend coincide with the positive departures of the PIC, especially in the area around Xinjiang (Fig. 4 (a), (e)). If comparing Fig. 4 (a), (c), and (e), we can find that the patterns in Fig. 4(a), (c) are similar in mid-latitudes, so does in high latitudes and Mediterranean for Fig. 4 (a), (e). In consequence, big positive departures near Ural mountain and around Xinjiang in Fig. 4 (a) are attributed to both the trend and the PIC.

For January case the PIC in mid-latitude (Fig. 4 (d)) is similar to that in Fig. 4 (b), for example, in northwest Europe, Caspian Sea, Salty Sea and the Central Asia, with big positive departures. However, discrepancies appear in Xinjiang and high latitudes between 45° E—90° E. As for the trend distribution (Fig. 4 (f)), the negative trends appear along a belt across the Mediterranean, Caspian Sea and Salty Sea, where most of the positive trends are distributed in high latitudes and Xinjiang about. It reveals that the large scale augment of the air humidity above Xinjiang and high latitudes (Fig. 4 (a)) is mainly caused by the wet trend coupling with the rapid warming there, while the positive departures in mid-latitude are attributed to the PIC of the atmospheric water vapor content. Hence, the departures of the SVP or PW fields result from both the wet trend and the PIC of the column water vapor content.

## 6 Discussion and conclusion

The reanalysis data and observation studies above have shown that the main water vapor sources of Xinjiang are situated in its west direction, and they are the Mediterranean, Black Sea, Caspian Sea, the North Atlantic and the Arctic sea, of which the Mediterranean and Caspian Sea are sources for January and April, the Black Sea and Caspian Sea are for October, and the North Atlantic and Arctic sea are for July, respectively. In the recent 14 years, more water vapor comes from relatively high latitudes due to the increase of the air column vapor content in January and July. The vapor coming from the Mediterranean has been reduced due to the WVT direction change, and the air above it has become drier, with less column vapor than the previous 14 years. The analysis of surface vapor pressure not only confirms the investigation results for column vapor content or PW, but also reveals that the column vapor augment during 1987—2000 is mainly attributed to the wet trend in connection with global warming, especially the rapid warming in high latitudes. Moreover, the maximal or minimal centers of the vapor departures in the period usually result from the overlap of the trends and the pure interdecadal changes in almost the same phase.

The warming and wet tendency in high latitudes is a very important climate implication, which makes boreal water vapor sources in recent 14 years more important to the Xinjiang region, because the water vapor transport from high latitudes to Xinjiang would increase even if there is no any change on climate wind field. It is clear that water vapor transport from high latitudes to Xinjiang is more efficient than that from the subtropical zone. Moreover, the wet tendency in high latitudes also implies that more water vapor could joint the transient eddies before entering Xinjiang, which would obviously increase the humidity and rainfall in Xinjiang. Meanwhile, the importance of the Mediterranean, a key vapor source for Xinjiang once a time, has become declining due to the decrease of its water vapor transport together with climate drying around there.

Finally, if only considering the stationary water vapor transport change, it is not sufficient to interpret the physical causes to Xinjiang climate transition since the mid-1980s. The transient eddy transport should be included too for further investigation in the near future.

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