The Influence of Large-Scale Circulation on the Summer Hydrological Cycle in the Haihe River Basin of China*

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(Received April 2, 2010; in final form March 28, 2011)

ABSTRACT

In this study, we focus on changes in three important components of the hydrological-cycle in the Haihe River basin (HRB) during 1957–2005: precipitation (Prep), actual evaportranspiration (ETa), and pan evaporation (PE)– a measure of potential evaporation. The changes in these components have been evaluated in relation to changes in the East Asian summer monsoon.

Summer Prep for the whole basin has decreased significantly during 1957–2005. Recent weakening of the convergence of the integrated water vapor flux, in combination with a change from cyclonic-like large-scale circulation conditions to anti-cyclonic-like conditions, led to the decrease in the summer Prep in the HRB.

ETa is positively correlated with Prep on the interannual timescale. On longer timescales, however, ETa is less dependent on Prep or the large-scale circulation. We found negative trends in ETa when the ERA40 reanalysis data were used, but positive trends in ETa when the NCEP/NCAR reanalysis data were used.

PE declined during the period 1957–2001. The declining of PE could be explained by a combination of declining solar radiation and declining surface wind. However, the declining solar radiation may itself be related to the weakening winds, due to weaker dispersion of pollution. If so, the downward trend of PE may be mainly caused by weakening winds.

Key words: hydrological cycle, runoff, Lamb-Jenkinson classification, circulation, Haihe River basin (HRB)

Citation: Ou Tinghai, Liu Yanxiang, Chen Deliang, et al., 2011: The influence of large-scale circulation on the summer hydrological cycle in the Haihe River basin of China. *Acta Meteor. Sinica*, **25**(4), 517–526, doi: 10.1007/s13351-011-0410-3.

1. Introduction

The Haihe River basin (HRB) is located in the northern-most part of China (Ou and Qian, 2006), where the largest portion of precipitation (Prep) happens in summertime. There is a well-documented shortage of available water in the HRB (Shao and Yang, 2007; Xia and Zhang, 2008). This problem is becoming more severe as water demand increases in the HRB (Ren et al., 2002), especially after the drastic deceases in Prep and runoff in the late 20th century (Liu et al., 2004b; Zhai et al., 2005; Gao et al., 2007). The issue of how water resources in the HRB should be managed is very important. To study the changing local climate and the influence of variations in circulation on the hydrological cycle in the HRB may help to understand the changing water resource, and thus help to manage the water resource in the HRB.

Following the downward trend in the global summer monsoon (Wang and Ding, 2006; Zhou et al., 2008a, b), the East Asian summer monsoon system has been weakening since the late 1970s (Hu, 1997; Wang, 2001; Guo et al., 2003; Hu et al., 2003; Wang and Ding, 2006; Yu et al., 2004; Xu et al., 2006; Zhou

*Supported by the National Basic Research and Development (973) Program of China (2006CB403404) and National Natural Science Foundation of China (40675038).

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et al., 2009a, b; Li et al., 2010), which has led to significant changes in rainfall over East China, generally referred to as southern flooding and northern drought. Wetter conditions in the Yangtze River valley and drier conditions in the Yellow River valley (Yatagai and Yasunari, 1994; Nitta and Hu, 1996; Weng et al., 1999; Xu, 2001; Hu et al., 2003; Yu and Zhou, 2007; Li et al., 2008) were observed. More specifically, the water vapor transport to the HRB decreased, resulting in decreasing summer Prep (Wei et al., 2005; Zhang et al., 2008). Due to the decreasing annual Prep in the HRB (Zhai et al., 2005; Gao et al., 2007), the annual river runoff significantly decreased in this region (Ren et al., 2002; Liu et al., 2004b; Yang and Tian, 2009). Both the annual potential evapotranspiration and the annual actual evapotranspiration (ETa) decreased in this region during 1960–2002 (Gao et al., 2006, 2007). No significant trend of ETa is found for 1960–2002 or 1951–2003 (Gao et al., 2007; Ni et al., 2007). The potential evapotranspiration and Prep in the summer season also decreased in the HRB (Wei et al., 2005; Gao et al., 2006).

The summer season is one of the most important periods for the water resource in the HRB when a large fraction of Prep and runoff occurs. The main objective of this paper is to more clearly understand the influence of the weakened East Asian summer monsoon on the summer hydrological cycle in the HRB. Changes in three important parts of the hydrological cycle, i.e., Prep, ETa, and potential evaporation, and the influence of changes in East Asian summer monsoon were evaluated. Recent changes in local climate, in the large-scale circulation background conditions (cyclonic-like or anti-cyclonic-like conditions), and in local water vapor divergence were examined.

The rest of this paper is organized as following. The data and methods used in this study are introduced in Section 2. The results are presented in Section 3. Some discussion follows in Section 4. Section 5 gives a summary of the conclusions.

2. Data and methods

2.1 Study region

Figure 1 shows the location of the Haihe River

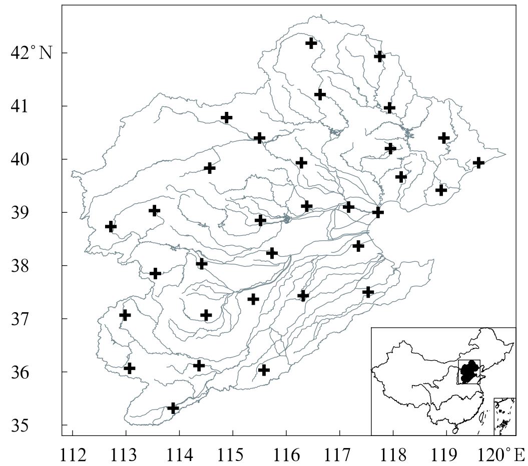

Fig. 1. Location of meteorological stations in the HRB.

system and the meteorological stations. The total annual Prep is 556 mm and the summer (June-July-August) total Prep is 380 mm, which is 68% of the annual total. The summer runoff is about 48% of the annual total. This study will focus on the summer period.

The annual mean total water resource of the HRB is 41.9 billion m^3. This is 335 m^3 per person, which is less than 1/6 of the mean water resource per person for entire China, and 1/24 of the mean water resource per person for the whole world (Xia et al., 2003). More attention needs to be paid to the water resource problem in the HRB. To study the influence of changes in circulation on the hydrological cycle in the HRB may improve our understanding of the long-term changes in water availability, which may help resolve the water resource problem in this region.

2.2 Meteorological data

In this study, gridded daily Prep data (Chen et al., 2010) for 1957–2005 have been used to evaluate the variation of the regional mean precipitation in the HRB. By using gridded Prep data, the spatial pattern of Prep anomaly for a selected day can be easily drawn. Thirty-one stations with daily mean temperature at 2 m (Tm), wind speed (WS), relative humidity (RH), and sunshine duration (SUN) data have also been used to study the variation of local climate. The widely used small-pan evaporation (PE) (Liu et al., 2004a; Chen et al., 2005; Chu et al., 2010), an indicator of potential evapotranspiration, has been used to study the variation of potential evaportranspiration in the HRB.

2.3 Reanalysis data and atmospheric water budget

In order to study the variations of large-scale circulation, water vapor transport and ETa, the surface pressure (p_s), u, v, and specific humidity (q) data were extracted from the NCEP/NCAR reanalysis dataset (Kalnaya et al., 1996; Kistler et al., 2000). As pointed out by Zhou and Yu (2005), the water vapor transport derived from the NCEP/NCAR reanalysis is stronger than that derived from ERA40, especially at low levels. Generally these two datasets, NCEP/NCAR and ERA40, give a similar picture of the water vapor transport associated with anomalous summer rainfall patterns in China (Zhou and Yu, 2005). ERA40 u, v, and q (Uppala et al., 2005) combined with p_s of NCEP/NCAR has been used to derive the ETa of ERA40.

For a selected region, the equation of vertically integrated atmospheric water balance can be written as:

$$\mathrm{Prep} - \mathrm{ETa} = -\frac{\partial W}{\partial t} - \nabla_h \boldsymbol{Q}, \tag{1}$$

where Prep is the precipitation, ETa is the actual evapotranspiration, W is total water vapor content, and $\nabla_h \boldsymbol{Q}$ is the divergence of vertically integrated water vapor flux $\boldsymbol{Q}$, which can in turn be written as:

$$\boldsymbol{Q} = -\frac{1}{g}\int_{p_\mathrm{s}}^{0} q\boldsymbol{v}\mathrm{d}p, \tag{2}$$

where q is specific humidity, $\boldsymbol{v}$ is the horizontal wind vector, p is pressure, p_s is the surface pressure, and g is the acceleration due to gravity. Since there is no specific humidity available above 300 hPa in the NCEP/NCAR reanalysis, and the maximum value of the neglected water vapor above 300 hPa is limited to within 2–3 cm yr^{-1} in terms of the freshwater flux (Zhou, 2003), the water vapor flux was calculated as:

$$\boldsymbol{Q} = -\frac{1}{g}\int_{p_\mathrm{s}}^{300} q\boldsymbol{v}\mathrm{d}p. \tag{3}$$

According to Zhai and Robert (1997), the change of summer total water vapor content in northern China is less than 3% (10 yr)$^{-1}$ (< 1 mm (10 yr)$^{-1}$), which is much smaller than the $\nabla_h \boldsymbol{Q}$ term. Thus, Eq. (1) can be simplified as:

$$\overline{\mathrm{Prep}} - \overline{\mathrm{ETa}} \cong -\overline{\nabla_h \boldsymbol{Q}}. \tag{4}$$

Then the evapotranspiration can be estimated as:

$$\overline{\mathrm{ETa}} \cong \overline{\mathrm{Prep}} + \overline{\nabla_h \boldsymbol{Q}}. \tag{5}$$

2.4 Lamb-Jenkinson circulation classification

The classification of circulation is based the manual scheme developed by Lamb (1950) for the British Isles, which was automated by Jenkinson and Collison (1977) by defining a number of indices and classification rules. This auto classification method has been widely used in Sweden (Chen, 2000; Linderson, 2001), and more recently in China (Ou, 2005; Jia et al., 2006; Zhu et al., 2007). Using the Jenkinson and Collison (1977) method, we get 6 indices calculated on 16 data grid points shown in Fig. 2. These include a westerly (zonal) wind index, southerly (meridional) wind index, and indices that indicate shear vorticity:

$$\mathrm{UI} = [p(12) + p(13) - p(4) - p(5)]/2, \tag{6}$$

$$\mathrm{VI} = a[p(5) + 2p(9) + p(13) - p(4) - 2p(8) - p(12)]/4, \tag{7}$$

$$\mathrm{WSI} = \sqrt{\mathrm{UI}^2 + \mathrm{VI}^2}, \tag{8}$$

$$\mathrm{VorIu} = b1[p(15) + p(16) - p(8) - p(9)]/2 - b2[p(8) + p(9) - p(1) - p(2)]/2, \tag{9}$$

$$\mathrm{VorIv} = c[p(6) + 2p(10) + p(14) - p(5) - 2(p) - p(13) - p(4) - 2p(8) - p(12) + p(3) + 2p(7) + p(11)]/4, \tag{10}$$

$$\mathrm{VorI} = \mathrm{VorIu} + \mathrm{VorIv}, \tag{11}$$

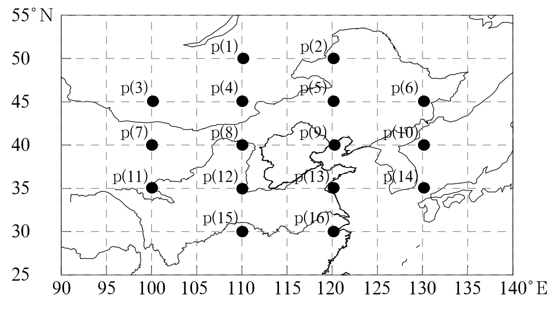

Fig. 2. Map showing the grid points used in the Lamb-Jenkinson circulation classification scheme.

where $p(n)$ is the mean sea level pressure (MSLP) at grid point n, UI and VI are indices indicating westerly (zonal) and southerly (meridional) wind respectively, WSI is the index that combines the two wind components; VorIu and VorIv are the two indices indicating westerly and southerly shear vorticity. VorI is the index indicating the total shear vorticity. The latter can be used to indicate the basic condition of large-scale circulation: cyclonic-like or anti-cyclonic-like conditions with positive or negative VorI respectively. All these indices have units of hPa per 10° latitude at the latitude of the center point. The constants are calculated according to the difference of longitude distance at the determined latitude. The formulas for calculating these constants are as follows,

$$\begin{cases} a = 1/\cos\varphi, \\ b1 = \sin\varphi/\sin(\varphi - 5), \\ b2 = \sin\varphi/\sin(\varphi + 5), \\ c = 1/2\cos^2\varphi. \end{cases} \tag{12}$$

In this paper, the latitude of center point in the HRB is fixed at $\varphi = 40°$N.

3. Results

3.1 Changes in local climate variables

The variations in local climate variables Prep, WS, Tm, RH, SUN, and PE during 1957–2005 are shown in Figs. 3a-f, and the trends can be found in Table 1. We found that summer Prep in the HRB decreased significantly during 1957–2005, with a downward trend of 18.4 mm (10 yr)$^{-1}$ (Fig. 3a). The downward trend is clear during the late 1950s and early 1980s while there was a slight increase during the early 1980s to late 1990s, after which the summer Prep continued to decrease. For PE (Fig. 3f), there was also a significant decrease during 1957–2005.

3.2 Changes in ETa

The ETa calculated using both ERA40 and NCEP/NCAR reanalysis data is shown in Fig. 4. Results of the two datasets coincide with each other quite well, except for the years 1960–1962. The trends of calculated ETa from the ERA40 and NCEP/NCAR reanalysis data are –5.8 mm (10 yr)$^{-1}$ and 8.7 mm (10 yr)$^{-1}$, respectively, during 1960–2002. Neither of these trends are statistically significant. The discrepancy between the results calculated from the ERA40 and NCEP/NCAR reanalysis datasets is discussed in Section 4.

Table 1. Trend (per 10 yr) of selected summer variables during 1957–2005 (1957–2001 for PE)

Prep (mm)	Tm (°C)	PE (mm)	WS (m s^{-1})	RH (%)	SUN (h)	Div$Q$ (mm)	ET (mm)
–18.4*	0.1	–18.7*	–0.1**	–0.3	–0.4**	22.5**	4.1

*Trend is significant at the 0.05 level (2-tailed).
**Trend is significant at the 0.01 level (2-tailed).

3.3 Changes in vertically-integrated water vapor convergence

The calculated convergence of vertically integrated water vapor flux $\overline{Q}$ (–Div$Q$) significantly weakened during 1957–2005 (Fig. 3g). The trend in divergence (Div$Q$) is 22.5 mm (10 yr)$^{-1}$, which is significant at the 0.01 level.

3.4 Changes in atmospheric circulation indices

The circulation indices all significantly decreased in summertime during 1957–2002 (Figs. 3i–l). The decrease in UI indicates decreased zonal transport and the decrease in VI indicates decreased meridional transport. The decreasing trend of VI was larger than the decreasing trend of UI, especially in the 1960s.

The index VorI indicates cyclonic-like or anti-cyclonic-like circulation for positive or negative VorI, respectively. Summer VorI decreased during 1957–2005 (Fig. 3l). This indicates the mean large-scale circulation has been changed from strongly convective to more weakly convective, that is, from cyclonic-like to anti-cyclonic-like conditions.

3.5 Relationships between variables and indices

3.5.1 Relation between summer Prep and circulation

Correlation coefficients between the local climate variables and the large-scale indices are shown in Table 2. The summer Prep, one of the most important components of the hydrologic cycle, is highly correlated with the variations of VorI (vorticity), VI

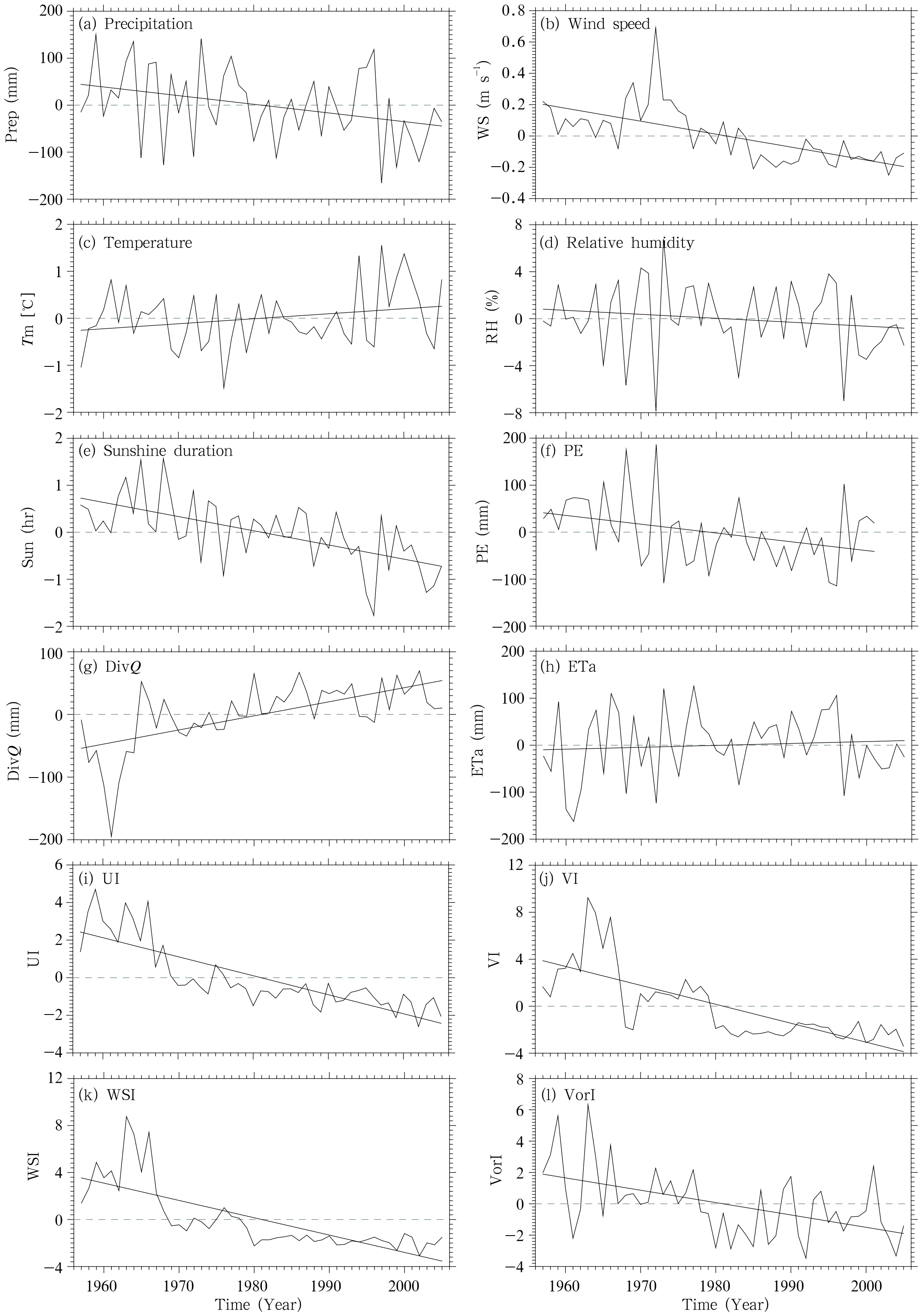

Fig. 3. Changes of (a) summer mean precipitation (Prep), (b) wind speed (WS), (c) mean temperature (Tm), (d) relative humidity (RH), (e) sunshine duration (SUN), and (f) Pan evaporation (PE) averaged from the observations, and (g) calculated water vapor divergence (Div$Q$), (h) actual evapotranspiration (ETa), and (i–l) four circulation indices, UI, VI, WSI, and VorI, respectively, during 1957–2005 (1957–2001 for PE).

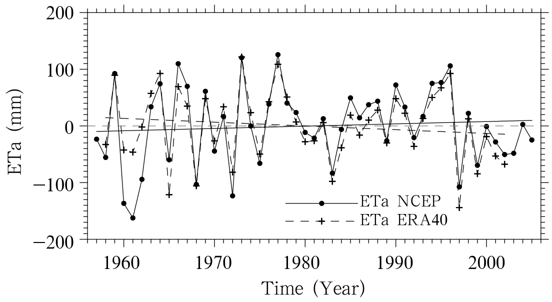

Fig. 4. Summer ETa anomaly calculated from NCEP (1957–2005) and ERA40 (1958–2002).

(water transport to the HRB from the south) and Div$Q$, with correlation coefficients being 0.39, 0.43, and –0.48, respectively. VI is highly correlated with VorI and Div$Q$, with the correlation coefficients being 0.60 and –0.56, respectively. But there is no significant correlation between VorI and Div$Q$ (correlation coefficient is –0.27, not significant at the 0.05 level). This implies that VorI and Div$Q$ alone, which indicate the large-scale circulation background and the local water vapor divergence, respectively, can be used to study the variation of Prep in summer in the HRB. The regression relationship is shown in Eq. (13). The reconstructed summer Prep (Rec Prep) is highly correlated with summer precipitation in the HRB (Fig. 5). Equation (13) suggests that cyclonic-like conditions combined with higher water vapor divergence in HRB will lead to larger Prep in the this region, vice versa.

$$\text{RecPrep} = 0.279 \times \text{VorI} - 0.403 \times \text{Div}Q. \qquad (13)$$

3.5.2 Potential evaporation

The potential evapotranspiration in the HRB is highly correlated with SUN, RH, WS, and Tm in summertime (see Table 2, or Gao et al., 2006). PE, as an indicator of potential evapotranspiration, can be simply reconstructed by using SUN, RH, WS and Tm.

Table 2. Correlations between variables and indices during 1957–2005 (1957–2001 for PE)

	Prep	UI	VI	WSI	VorI	Tm	PE	WS	RH	SUN	Div$Q$
UI	0.41**										
VI	0.43**	0.81**									
WSI	0.43**	0.93**	0.93**								
VorI	0.39**	0.65**	0.60**	0.67**							
Tm	–0.38**	–0.04	–0.08	0.01	–0.01						
PE	–0.57**	0.36*	0.21	0.31*	0.17	0.53**					
WS	–0.04	0.41**	0.41**	0.36*	0.39*	–0.09	0.57**				
RH	0.81**	0.11	0.21	0.12	0.11	–0.55**	–0.85**	–0.24			
SUN	–0.26	0.47**	0.41**	0.44**	0.34*	0.23	0.78**	0.57**	–0.45**		
DivQ	–0.48**	–0.64**	–0.56**	–0.59**	–0.27	0.06	–0.13	–0.36*	–0.27	–0.07	
ETa	0.77**	–0.01	0.07	0.03	0.24	–0.38**	–0.72**	–0.31*	0.71**	–0.34*	0.20

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

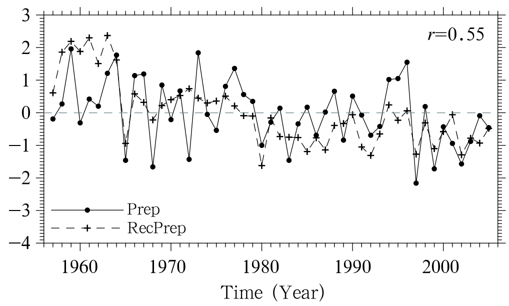

Fig. 5. Normalized summer precipitation (Prep) and reconstructed summer precipitation (RecPrep) during 1957–2005.

Stepwise regression was used to build a model of PE based on RH, WS, SUN, and Tm (Eq. (14)) (variables have been normalized). The correlation coefficient between reconstructed and measured PE was 0.96 (Fig. 6). From Eq. (14), it is seen that variations in PE are most strongly influenced by RH, which has the largest coefficient, with higher RH giving less PE, and vice versa. The influences of WS and SUN are of the same magnitude, and the influence of Tm is the smallest.

Combining the trends in Table 1 with the coefficients in Eq. (14), we find that the upward trend of Tm contributes +11.0 mm (10 yr)$^{-1}$ to the trend in

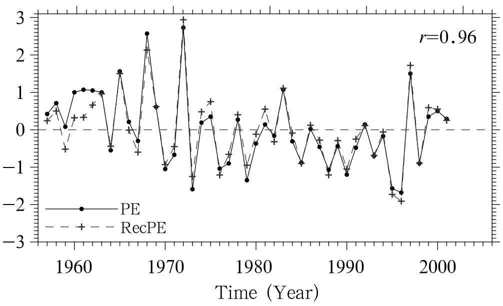

Fig. 6. Normalized summer total pan evaporation (PE) and reconstructed pan evaporation (RecPE) during 1957–2001.

PE over 1957–2005; the downward trend of RH contributes +68.5 mm (10 yr)$^{-1}$; the decrease of surface WS contributes –14.5 mm (10 yr)$^{-1}$; and declining SUN contributes –57.8 mm (10 yr)$^{-1}$. Note that the trend in PE listed in Table 1 is for the period 1957–2001 so that result is not precisely comparable with the trend contributions given here.

$$\text{RecPE} = -0.476 \times \text{RH} + 0.302 \times \text{WS} + 0.301 \times \text{SUN} + 0.234 \times T\text{m}. \quad (14)$$

4. Discussion

4.1 Changes in Prep

The trend in Div$Q$ was found to be 22.5 mm (10 yr)$^{-1}$. From Eq. (4), this may have caused the decreased summer Prep in the HRB (Wei et al., 2005). The changes of calculated ETa were comparatively small compared to the trends in summer Prep and Div$Q$. This confirms that the decrease in summer Prep in the HRB was not caused by a decline in local-scale evaportranspiration and precipitation recycling, but by changes in larger-scale water-vapor flux or flux convergence (Wei et al., 2005; Zhang et al., 2008).

In addition, the downward trend of UI and especially VI probably led to a weakening of water vapor transport to the HRB. This is consistent with the results from Wei et al. (2005), who found that the water vapor transport into and out of the HRB had decreased.

Finally, the mean large-scale circulation has been changed from strongly convective to weakly convective, that is, from cyclonic-like to anti-cyclonic-like conditions. This will also depress the formation of precipitation.

Thus, we find that a combination of factors have contributed to the decline in Prep in the HRB during 1957–2005.

4.2 Changes in PE

As discussed in Section 3, the trends in Tm and RH would both have led to increased PE, and cannot explain the downward trend of PE. The downward trend of PE is caused by the combined effect of declining WS and SUN.

Recently, the surface WS has significantly weakened over China (Fu et al., 2010; Gao et al., 2010; Jiang et al., 2010). The downward trend of mean surface WS over the HRB coincides with the WS trend over the whole China. In addition, we found that the large-scale wind speed index WSI weakened during 1957–2005. The weakening of the large-scale wind may give rise to the decrease of surface WS in this region (surface WS is significantly correlated with circulation-scale wind speed). This contributed to the decreasing PE in the HRB.

On the other hand, the HRB is one of the most heavily polluted regions in China (Qian et al., 2009; Tie and Cao, 2009), and increased pollution levels may have caused the decrease in SUN. However, the decreased wind transport may have reduced the atmospheric dispersion of the pollution in the region, which may also have incurred a decrease in SUN: this idea was proposed by Yang et al. (2009a, b), who noted the spatial and temporal correlations between low-wind speed and decreased SUN.

Either way, the decrease of PE was influenced by the weakening of the large-scale circulation, and the declining wind speed alone suppressed the potential evaportranspiration in HRB to some extent.

4.3 Changes in ETa

The trend in ETa calculated from ERA40 and reported in this paper is similar to the results from Gao (2010), who found the downward trend in summer ETa in the HRB during 1960–2002 to be –6.1 mm (10 yr)$^{-1}$ by using an advection aridity model or –7.0 mm (10 yr)$^{-1}$ from a water balance approach.

As pointed out by Zhou and Yu (2005), the water vapor transport derived from the NCEP/NCAR reanalysis is stronger than that derived from ERA40, especially at low levels. The difference between the ETa trends from the ERA40 and NCEP/NCAR datasets is mainly caused by the large difference during 1960–1962. The exact cause of the discrepancy during 1960–1962 requires a further analysis.

5. Conclusions

During the last 40 years, Prep and runoff significantly decreased in the HRB (Liu et al., 2004b; Wei et al., 2005), and the water shortage problem has aggravated with the increasing demands on the usage of water resource (Ren et al., 2002). This work focused on the variations in local climate and the influences of changes in the large-scale circulation on the hydrological cycle in the HRB. Some conclusions can be drawn as follows:

1) The summer Prep dramatically decreased during the last 40 years in the HRB, which led to the decreasing of runoff. The observed Tm increased during the same time, while PE, RH, WS, and SUN significantly decreased during 1957–2005.

2) Zonal and meridional transport of water vapor to the HRB significantly decreased during 1957–2005. The cyclonic-like conditions of large-scale circulation over the HRB have been weakened during 1957–2005, leading to more anticyclonic-like conditions. The convergence of vertically integrated water vapor flux also significantly weakened during 1957–2005.

3) Recent weakening of the convergence of integrated water vapor and more anticyclonic-like large-scale circulation conditions resulted in the decrease of summer Prep in the HRB.

4) ETa is highly correlated with Prep, but summer ETa has not changed significantly during 1957–2005, which indicates that the interdecadal change of ETa is less influenced by the change of large-scale circulation. The estimated ETa from ERA40 and NCEP/NCAR reanalysis datasets coincides with each other quite well, except for the years 1960–1962. The calculated ETa during 1960–1962 needs some further investigation.

5) Variation of PE can be successfully reconstructed by SUN, RH, WS, and Tm. The declining PE is caused by a combination of declining SUN and declining WS. However, the downward trend of SUN may be related to the weakening of WS. If so, the downward trend of PE is mainly influenced by the weakening of WS.

Acknowledgments. The authors would like to thank the reviewers for their comments that have helped improve the manuscript.

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