Contributions of Local and Remote Atmospheric Moisture Fluxes to East China Precipitation Estimated from CRA-40 Reanalysis

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ABSTRACT

China Meteorological Administration (CMA) recently released its 40-yr (1979–2018) global Chinese reanalysis (CRA-40) dataset. To assess performance of the CRA-40 data in quantifying the regional water cycle, contributions of local and remote atmospheric moisture fluxes to precipitation in East China derived from CRA-40 are compared with those derived from the ECMWF reanalysis version 5 (ERA-5). Observed precipitation and evaporation data are also used for validation. As for mean precipitation, CRA-40 matches the observation better in winter and spring than in summer, with a larger wet bias (1.41 mm day⁻¹) in summer than that in ERA-5 (0.97 mm day⁻¹), particularly over South China. The conservation of atmospheric water vapor over East China measured by CRA-40 is comparable to that of ERA-5. Both reanalyses show a dominant role of the remote moisture transport in the East China precipitation. In comparison, the annual precipitation induced by the moisture influx from the west of the study domain in CRA-40 is 80 mm less than that in ERA-5. The recycling ratio of annual mean precipitation in CRA-40 is approximately 21.1%, slightly larger than that in ERA-5 (20.1%). The maximum difference of each hydrological component between the two datasets appears in the summer horizontal moisture influx (3.57 × 10⁷ kg s⁻¹; ERA-5 is larger) and winter runoff (1.84 × 10⁷ kg s⁻¹; CRA-40 is larger). CRA-40 shows better performance than ERA-5 in capturing the interannual variability of precipitation over East China, as evinced by a higher correlation coefficient with the observation (0.77 versus 0.33). The trend of summer precipitation since 2011 is better reproduced in CRA-40. Both reanalyses show prominent contribution of the southern moisture influx to the interannual variation of precipitation. This study demonstrates the reliability of CRA-40 in representing the hydrological cycle over East China and provides a useful reference for future application of CRA-40 in water cycle studies.

Key words: 40-yr global Chinese reanalysis (CRA-40), precipitation recycling ratio, water vapor transport

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1. Introduction

East China is one of the world’s most populated regions, where the agricultural production and social economy are vulnerable to the precipitation variation. Excessive or deficit precipitation may lead to floods or droughts, causing great agricultural and economic losses (Zhang and Zhou, 2015; Liu et al., 2018). To better understand and forecast the variation of precipitation over East China, it is necessary to investigate and understand the moisture supply of precipitation in this region.

For a specific region, there are two moisture sources for precipitation: remote water vapor transport and local evaporation. East China is located within the monsoon area; its precipitation is greatly affected by the water vapor transport associated with the East Asian monsoon...
demann et al., 2008; Gimeno et al., 2010; Zhang et al., (Huang et al., 2004; Ding and Chan, 2005). Simmonds sources to regional precipitation (Kurita et al., 2003; So-

to obtain the relative contributions of different moisture

tion is from land, but ocean plays an important role in

Application of a moisture recycling model can help to

The quantification of regional water cycle relies heav-

The data and methods used in this paper are introduced

2. Data and methods

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al., 2019); it is based on 4D-Var data assimilation using Cycle 41r2 of the Integrated Forecasting System (IFS), with 137 vertical levels and a top layer at approximately 0.01 hPa, and a horizontal resolution of 31 km (TL639). The variables used in this study include precipitation, evaporation, surface pressure, specific humidity, and meridional and zonal winds. All the variables are monthly means. Both datasets cover the period 1979–2018.

We also used the observed monthly precipitation data (CN05.1; Wu and Gao, 2013) from 1979 to 2018 to validate the precipitation in the two reanalysis datasets. CN05.1 is a gridded dataset interpolated from more than 2400 station observations over China, with a horizontal resolution of 0.25° × 0.25°. The observed evaporation utilized in this study is from a global 5-km monthly evaporation dataset produced with the revised surface energy balance algorithm (Chen et al., 2019). This dataset provides continuous high-resolution gridded global evaporation observations calculated by the Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature, normalized difference vegetation index (NDVI), global forest height, globe albedo, etc. To facilitate the comparison, all datasets are interpolated onto the grid of CRA-40 because the horizontal resolution of CRA-40 (34 km) is slightly lower than that of ERA-5 (31 km). We also interpolated ERA-5 data onto the grid of CRA-40, and the results are almost the same with those of CRA-40 interpolated onto the grid of ERA-5. Thus, we only display the results by interpolating ERA-5 onto the grid of CRA-40.

### 2.2 Methods

In this study, we used the two-dimensional atmospheric moisture fluxes model from Brubaker (Brubaker et al., 1993) to calculate the precipitation recycling ratio over East China. This model is based on the mass conservation of atmospheric water vapor:

\[
\frac{\partial Q}{\partial t} = -\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) + E - P, \tag{1}
\]

where \(Q\) is the vertically integrated atmospheric water vapor (kg m\(^{-2}\)); \(F_u\) and \(F_v\) are zonal and meridional vertically integrated horizontal moisture fluxes (kg m\(^{-1}\) s\(^{-1}\)); and \(E\) and \(P\) are the evaporation and precipitation (kg m\(^{-2}\) s\(^{-1}\)), respectively. In this study, \(F_u\) and \(F_v\) are calculated based on the following equations:

\[
F_u(x, y, t) = \frac{1}{g} \int_{p_s}^{100} q(x, y, p, t) U(x, y, p, t) \, dp, \tag{2}
\]

\[
F_v(x, y, t) = \frac{1}{g} \int_{p_s}^{100} q(x, y, p, t) V(x, y, p, t) \, dp, \tag{3}
\]

where \(U\) and \(V\) are zonal and meridional winds, respectively; \(q\) is specific humidity; \(p_s\) is surface pressure; and \(g\) is acceleration of gravity.

At relatively long timescales, the model assumes that the moisture content in the atmosphere remains constant, i.e., \(\frac{\partial Q}{\partial t} = 0\). Equation (1) can then be written as

\[
\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) = E - P. \tag{4}
\]

In this model, the atmosphere is assumed to be well mixed so that the proportion of advected and locally evaporated moisture in the atmosphere is the same as that in precipitation within the region:

\[
P_a = \frac{Q_a}{Q}, \quad P_e = \frac{Q_e}{Q}, \tag{5}
\]

where \(P_a\) and \(P_e\) are components of precipitation arising from advected moisture and local evaporation, while \(Q_a\) and \(Q_e\) are components of atmospheric moisture arising from advected moisture and local evaporation, respectively. Therefore, the mass conservation for the advected portion of precipitation can be obtained as

\[
\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) = -P_a, \tag{6}
\]

where \(F_u\) and \(F_v\) are the vertically integrated horizontal moisture flux of advected moisture.

It is assumed that \(E\), \(P\), and \(P_a\) are constant over the study region A. The areal integrals of Eqs. (4) and (6) can be written as

\[
\nabla \cdot F|_A = F^{\text{out}} - F^{\text{in}} = (E - P) \times S, \tag{7}
\]

\[
\nabla \cdot F|_a = F_a^{\text{out}} - F_a^{\text{in}} = -P_a \times S, \tag{8}
\]

where \(\nabla \cdot F|_A\) and \(\nabla \cdot F|_a\) are the divergence of horizontal moisture flux and the divergence of horizontal flux of advected moisture over region A; \(F^{\text{out}}\) and \(F^{\text{in}}\) are the horizontal moisture flux out of the region and the horizontal flux of advected moisture out of the region; \(F^{\text{in}}\) is the horizontal moisture flux into the region; and \(S\) is the areal size of region A. The average horizontal moisture fluxes can be taken as the arithmetic mean of the influx and outflux:

\[
F = \frac{F^{\text{in}} + F^{\text{out}}}{2} = F^{\text{in}} + \frac{(E - P) \times S}{2}, \tag{9}
\]

\[
\bar{F}_a = \frac{F_a^{\text{in}} + F_a^{\text{out}}}{2} = F^{\text{in}} - \frac{P_a \times S}{2}. \tag{10}
\]

As before, under the premise that the atmosphere is fully mixed, the precipitation recycling ratio \(\rho\) can be derived by applying Eqs. (9) and (10) to \(\frac{P_a}{P} = \frac{\bar{F}_a}{\bar{F}}\) as
follows,

$$\rho = \frac{E \times S}{E \times S + 2F_{in}}. \quad (11)$$

According to Eq. (11), the proportion of precipitation arising from advected moisture in total precipitation within a region, i.e., $\alpha$, can be calculated as $1 - \rho$:

$$\alpha = \frac{P_a}{P} = 1 - \rho = \frac{2F_{in}}{E \times S + 2F_{in}}. \quad (12)$$

Then, the precipitation induced by local evaporation ($P_e$) and remote water vapor transport ($P_a$) can be obtained as

$$P_e = P \times \rho, \quad (13)$$

$$P_a = P \times \alpha. \quad (14)$$

Furthermore, we also calculated the precipitation originated from advected moisture through the western, eastern, northern, and southern boundaries ($P_W$, $P_E$, $P_N$, and $P_S$) of the study domain, following the methods of Guo et al. (2018) and obtain

$$\alpha_W = \frac{2F_{in}}{E \times S + 2F_{in}}; \quad \alpha_E = \frac{2F_{in}}{E \times S + 2F_{in}}; \quad (15)$$

$$\alpha_N = \frac{2F_{in}}{E \times S + 2F_{in}}; \quad \alpha_S = \frac{2F_{in}}{E \times S + 2F_{in}}.$$  

Here, $F_{in}$ is the horizontal moisture flux into the region through western boundary, and $\alpha_W$ is the contribution of moisture from western boundary to the local precipitation. Similar methods are applied to other three directions, and $P_W$, $P_E$, $P_N$, and $P_S$ are obtained by

$$P_W = P \times \alpha_W; \quad P_E = P \times \alpha_E; \quad P_N = P \times \alpha_N; \quad P_S = P \times \alpha_S. \quad (16)$$

### 3. Results

#### 3.1 Contributions of local and remote moisture fluxes to climatological mean precipitation

We first examine the performance of CRA-40 in capturing the annual cycles of precipitation, evaporation, and convergence of the vertically integrated moisture flux averaged over East China (Fig. 1). The annual cycle of precipitation in CN05.1 shows a single peak in June (5.8 mm day$^{-1}$). CRA-40 can capture the annual cycle of East China precipitation but peaks in July. It matches the observation well in winter and spring but exceeds observation by a larger margin than that in ERA-5 during boreal summer, especially in August, with the difference ranging from 0.03 to 1.9 mm day$^{-1}$. By dividing the target region into three regions: South China (21°–27°N), Yangtze River basin (27°–33°N), and North China (33°–41°N), we found that the one-month phase lag of CRA-40 precipitation compared with CN05.1 mainly comes from the Yangtze River basin. The precipitation in the Yangtze River basin of CRA-40 peaks in July but that of observation peaks in June. The seasonal cycles of CRA-40 precipitation in the other two areas are consistent with observation (figures omitted). In comparison, ERA-5 well presents the rainfall peak in June, but the
magnitude is larger than the observation throughout the year, with the difference ranging from 0.4 to 1.1 mm day\(^{-1}\). The annual cycle of evaporation in observation shows a single peak in July (2.93 mm day\(^{-1}\)). Both CRA-40 and ERA-5 can reveal this feature well, but overestimate the evaporation amount. The biases in CRA-40 (0.52–1.49 mm day\(^{-1}\)) are larger than that in ERA-5 (0.42–1.46 mm day\(^{-1}\)). The general characteristics of annual cycle of moisture flux convergence in CRA-40 are highly consistent with those in ERA-5 (e.g., single peak in July). However, moisture flux convergence in CRA-40 is smaller in quantity than that in ERA-5 all year around. Both of the two reanalysis datasets show that, over East China, precipitation exceeds evaporation from February to September, manifested as moisture convergence, indicating that East China is a water gaining region during these months.

We further examine the CRA-40 data in capturing seasonal differences of the regional hydrological cycle. This is crucial for East China, a region controlled by strong monsoon circulation (Zhou et al., 2008). In summer, the observed precipitation over East China increases from northwest to southeast, with the maximum (9–10 mm day\(^{-1}\)) in the coastal South China and the minimum (1–3 mm day\(^{-1}\)) in Inner Mongolia (Fig. 2a). Both reanalysis datasets have captured the distribution of precipitation, but the precipitation amount of CRA-40 in South China is significantly larger than the observation (Figs. 2b, c). The pattern correlation coefficients between summer precipitation in reanalysis datasets and observation are 0.92 for CRA-40 and 0.98 for ERA-5, respectively. The main differences between the two reanalysis datasets are visible in South China, where the precipitation in CRA-40 is more than 8 mm day\(^{-1}\) larger than that in ERA-5 (Fig. 2g). In winter, general patterns of precipitation in CRA-40 and ERA-5 are both similar to that in CN05.1, where the maximum (3–4 mm day\(^{-1}\)) presents in the middle and lower reaches of the Yangtze River. For ERA-5, the regional mean precipitation bias is larger than that in CRA-40, which is 0.91 and 0.34 mm day\(^{-1}\) for summer and winter, respectively. The summer precipitation of ERA-5 shows uniformly distributed wet biases, and the winter precipitation exhibits a relatively large wet bias in the southwest of East China. We also select four more reanalysis datasets: the Japanese 55-yr reanalysis (JRA55), NCEP Climate Forecast System reanalysis (CFSR), NCEP/NCAR reanalysis version 1, and NCEP/NCAR reanalysis version 2, and compare their performance in spatial distribution of annual mean precipitation with CRA-40 and ERA-5. The results (figures omitted) show that all reanalyses can capture the distribution of climatological precipitation. ERA-5 is better in presenting the large value in the middle and lower reaches of the Yangtze River and South China as in CN05.1, compared to other reanalyses. The distribution in CRA-40 is more similar to that in CFSR. All reanalyses overestimate the precipitation in South China.

For evaporation, because the observed gridded dataset is scarce and it is not the focus of this study, we utilize the dataset mentioned in Section 2.1 for a general comparison of the spatial distribution of evaporation in CRA-40 and ERA-5 (figures omitted). The pattern correlation coefficients between climatological summer (winter) evaporation in reanalysis datasets and observation are 0.73 (0.86) for CRA-40 and 0.86 (0.89) for ERA-5, respectively. Both CRA-40 and ERA-5 overestimate the evaporation over East China in summer and winter. The bias in CRA-40 is larger than that in ERA-5, especially in the southern part of East China.

The spatial distributions of vertically integrated water vapor transport in the two reanalysis datasets are also exhibited in Fig. 2. The water vapor transport characteristics of the two reanalysis datasets are accordant with each other in both summer and winter. In summer, water vapor over East China is mainly imported from southern boundary, transported by the East Asian summer monsoon and South Asian summer monsoon (Figs. 2b, c). CRA-40 shows northern transport anomalies compared with ERA-5 over East China, which increase from north to south (Fig. 2g). In other words, the summer monsoonal water vapor transport in CRA-40 is weaker than that in ERA-5. In winter, water vapor mainly comes from western boundary and is controlled by the westerlies. We further compare the role of wind and moisture (\(q\)) on the difference of water vapor transport between the two data-
sets. The results show that the weaker water vapor transport in CRA-40 is mainly caused by the weaker wind in CRA-40 relative to ERA-5, while the water vapor in CRA-40 can partly offset the discrepancy of wind (figures omitted).

We then examine the performance of CRA-40 in measuring water vapor budget. According to Eq. (4), on the monthly timescale, the loss of atmospheric water vapor (precipitation plus divergence of vertically integrated moisture flux, i.e., $P + \text{div}Q$) should be approxim-
ately equal to the gain of water vapor (evaporation, $E$) over East China. This is an important metric to evaluate the quality of any dataset in representing atmospheric water vapor conservation over a study region. Figure 4 shows scatter plots of $P + \text{div} \mathbf{Q}$ and $E$ in each month averaged over East China obtained from CRA-40 and ERA-5. It is seen that the two reanalysis datasets are approximately reasonable in depicting the conservation of atmospheric water vapor. The range of $P + \text{div} \mathbf{Q}$ is relative larger than that of $E$ in CRA-40. The root mean square error of $P + \text{div} \mathbf{Q}$ and $E$ in CRA-40 (0.75 mm day$^{-1}$) is slightly larger than that in ERA-5 (0.69 mm day$^{-1}$), but the correlation coefficient between the two terms in CRA-40 (0.87) is significantly larger than that in ERA-5 (0.68).

The precipitation recycling ratio ($\rho$) is a useful measure of regional hydrological cycle (Brubaker et al., 1993). To estimate the precipitation recycling ratio, evaporation and horizontal moisture flux into the region need to be derived based on Eq. (11). Since long-term continuous observations of the atmosphere are very hard to obtain, $\rho$ is generally calculated by use of reanalysis data (Guo and Wang, 2014; Hua et al., 2017; Guo et al., 2018; Yao et al., 2020). We compare all the hydrological cycle components derived from CRA-40 and ERA-5 in Fig. 5. CRA-40 well captures the climate mean characteristics of the moisture cycle over East China. 1) In comparison, $\rho$ derived from CRA-40 (22.34%) is approximately 4% larger than that from ERA-5 (18.16%) in summer and the difference is about 1% in winter. The larger evaporation

![Fig. 3. Distributions of the precipitation bias (mm day$^{-1}$) in (a, c) CRA-40 and (b, d) ERA-5 relative to the observation (obs) for (a, c) summer (JJA) and (b, d) winter (DJF) during 1979–2018.](image-url)
and $\rho$ in CRA-40 than those in ERA-5 demonstrate that the heavier summer precipitation in CRA-40 than ERA-5 (Fig. 1) is mainly from $P_e$. For the whole year, the mean annual $\rho$ over East China is 20.1% in ERA-5 and 21.1% in CRA-40, indicating that the mean precipitation is controlled by the remote water vapor transport. 2) The proportion of evaporated moisture falling in the same area as precipitation to total evaporation (defined as evaporation
recycling ratio) in CRA-40 (40%) is likewise larger than that in ERA-5 (36%) in summer. The evaporation recycling ratio in winter is smaller than that in summer, which is 13% in CRA-40 and 16% in ERA-5, respectively. 3) In summer, about 65% of the remote moisture influx to East China is converted to precipitation, and the remaining moisture directly flows out of the region in CRA-40. In ERA-5, only 57% of $F^m$ falls as precipitation in summer. Contrary to summer, the conversion ratio in winter in CRA-40 (24%) is smaller than that in ERA-5 (30%). 4) The maximum difference of each hydrological component between the two datasets appears in $F^m$ ($3.57 \times 10^7$ kg s$^{-1}$) in summer and runoff ($1.84 \times 10^7$ kg s$^{-1}$) in winter.

Moreover, to investigate from which direction the water vapor contributes the most to mean precipitation, we calculate the water vapor influx from each direction using the methods of Guo et al. (2018). Figure 6 shows the climate mean annual cycles of the contributions of moisture influx from different directions to precipitation, as well as from the local evaporation, in CRA-40 and ERA-5. It is found that the climate mean annual cycles of the contributions to precipitation from different moisture sources calculated by the two reanalysis datasets are very similar. The moisture influx via the western boundary (i.e., western moisture influx) dominates the mean precipitation from October to April (contributing 45%–65%), while the southern moisture influx is the major contributor in June, July, and August (JJA; contributing about 65%). In May, contributions of western and southern moisture influxes are comparable, which are both around 40%. It is worth noting that the local evaporated moisture dominates the mean precipitation in September when the contribution of local evaporation ($\rho$) reaches its maximum (about 40%). This suggests that the strength of the evaporation–precipitation coupling in September is relatively stronger than that in other months. Comparing the contribution of each moisture source in the two reanalysis datasets reveals that the contributions from northern boundary and local evaporation are greater and the contributions from western and eastern boundaries are smaller in CRA-40 than in ERA-5. For the contribution from southern boundary, it is relatively greater in CRA-40 than in ERA-5 during winter months, and the opposite during other months. The maximum difference between the two datasets occurs in August, during which the contribution of local evaporation in CRA-40 is 7% larger than that in ERA-5, and the contribution of southern influx is 7% smaller than that in ERA-5. For the annual total precipitation, southern moisture influx contributes most (about 40%), followed by western moisture influx (about 32%), as shown in both datasets. The main difference is that western moisture influx of ERA-5 produces about 80 mm more annual precipitation than that of CRA-40.

![Figure 6](image-url)

**Fig. 6.** Monthly variations of the contribution (a, c) in percentage and (b, d) in quantified value (mm day$^{-1}$) to precipitation by the moisture influxes from different directions of the study domain, as well as from local evaporation in (a, b) ERA-5 and (c, d) CRA-40 during 1979–2018.
3.2 Contributions of local and remote moisture fluxes to interannual variability of precipitation

In the above section, the contributions of local and remote moisture fluxes to climatological mean precipitation in ERA-5 and CRA-40 are investigated. Here, the main contributors of the moisture fluxes to interannual variability of precipitation in the two reanalysis datasets are explored and compared. Firstly, the interannual variability of precipitation over East China for 1979–2018 in each reanalysis dataset is examined by comparing with that in CN05.1, as shown in Fig. 7. The interannual variability of annual precipitation in CRA-40 has a high consistency with that in CN05.1, which fluctuates between 1979 and 1998, decreases significantly from 1998 to 2011, and increases substantially after 2011. The correlation coefficient between annual precipitation in CRA-40 and observed precipitation (0.77) is much larger than that for ERA-5 (0.33). ERA-5 cannot reveal the recovery of precipitation since 2011. The difference mainly arises in summer (Fig. 7b). The correlation coefficient between summer precipitation in CRA-40 and observed precipitation (0.72) is higher than that for ERA-5 (0.52). For winter precipitation, both of the two reanalysis datasets exhibit the interannual variation of the observed values well. In sum, the interannual variability of precipitation in CRA-40 shows a higher correlation with the observation than in ERA-5, particularly the summer precipitation variation since 2011.

To compare the relative contributions of local and remote moisture supply to the precipitation interannual variability, interannual variations of total precipitation, precipitation induced by local evaporation and remote water vapor transport, and $\rho$ averaged over East China for 1979–2018 in ERA-5 and CRA-40 are displayed in Fig. 8. The two reanalysis datasets both demonstrate that the remote water vapor transport dominates the precipitation interannual variability. The correlation coefficient between total precipitation and precipitation from remote moisture source is greater than 0.97 in both data-

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**Fig. 7.** Temporal evolution of precipitation ($P$) anomaly (mm day$^{-1}$) averaged over East China relative to the 1979–2018 mean for (a) annual, (b) summer, and (c) winter scenarios. The black, red, and blue lines represent the precipitation derived from CN05.1 (OBS), ERA-5, and CRA-40, respectively. The numbers in the brackets are correlation coefficients between the two reanalysis datasets and CN05.1.
sets. In addition, it can be found that the total precipitation shows a significant negative correlation with $\rho$ in both ERA-5 and CRA-40. The correlation coefficients between them in ERA-5 and CRA-40 are $-0.49$ and $-0.31$, respectively. The contribution of local evaporation to precipitation is significantly higher than for years with deficit precipitation, such as 2004 and 2011. This suggests that the contribution of local evaporated moisture is relative more important during a dry year than during a wet year. Meanwhile, the interannual variation of $\rho$ in ERA-5 and CRA-40 maintains a high level of agreement, of which the correlation coefficient is 0.93. The difference between the two datasets since 2011 is mainly caused by remote water vapor induced precipitation.

Figure 9 further shows the interannual variations of precipitation anomalies (relative to 1979–2018) induced by remote moisture influx from the four directions. In the two reanalyses, $P_W$ and $P_S$ are positively and significantly correlated with $P$, while $P_N$ and $P_E$ show no significant correlation with $P$. That is, the variations of annual total precipitation are primarily dominated by the western and southern moisture influxes. The correlation coefficient between $P_W$ and $P$ is 0.63 (0.80), while it is 0.71 (0.76) between $P_S$ and $P$, in CRA-40 (ERA-5). It is found that the annual precipitation contributed by southern moisture influx shows a higher correlation with total precipitation than that contributed by western moisture influx in CRA-40, contrary to the case in ERA-5. The difference between annual precipitation in CRA-40 and ERA-5 for 2011–2018 mainly comes from the positive anomalies of the southern influx induced precipitation in CRA-40, as indicated in Fig. 9.

The correlation coefficients between the moisture sources and precipitation in different seasons are presented in Table 1. By comparing with the contribution to mean precipitation in Fig. 6, the main contributor to mean precipitation is not necessarily the main contributor to precipitation interannual variability. In winter (December, January, and February, i.e., DJF) and spring (March, April, and May, i.e., MAM), all moisture resources except eastern influx play important roles in the interannual variation of precipitation, among which the southern influx and local evaporation are the major contributors (correlation coefficients are all above 0.70), though the major contributor to mean precipitation is the western influx. In addition, precipitation is positively correlated with southern and western influxes but negatively correlated with northern influx and evaporation. The difference between the two datasets is that the con-
tribution of northern moisture influx (−0.54) is greater than that of western influx (0.43) in CRA-40 during MAM. In summer (JJA) and autumn (September, October, and November; SON), major contributors to the precipitation interannual variability are both southern moisture influx in the two datasets. It is worth noting that the eastern moisture influx is also a notable contributor to SON precipitation interannual variability in ERA-5, which is, however, not found in CRA-40.

4. Conclusions

In this study, an evaluation on the hydrological cycle over East China in CRA-40 reanalysis data is carried out in comparison with the ERA-5 reanalysis data and the observation. The contributions of local and remote atmospheric moisture fluxes to the climate mean and interannual variability of precipitation over East China during 1979–2018 are examined and analyzed. The reliability of CRA-40 in representing the hydrological cycle of East China is evaluated. The main findings are summarized as follows.

(1) The climate mean annual variations of hydrological cycle components averaged over East China all show a single peak in boreal summer. The climate mean precipitation in CRA-40 matches the observation better in winter and spring than in summer, with a relatively larger wet bias (1.41 mm day\(^{-1}\)) in summer than that in ERA-5 (0.97 mm day\(^{-1}\)), particularly over South China. The annual change of precipitation in CRA-40 shows a one-month phase lag over the Yangtze River basin, compared with observation. The mean annual evaporation in CRA-40 is 75 mm larger than that in ERA-5, while the

| Table 1. Correlation coefficients between the moisture sources and precipitation in different seasons during 1979–2018 derived from ERA-5 and CRA-40; \(F_W\), \(F_E\), \(F_S\), and \(F_N\) are the western, eastern, southern, and northern remote water vapor influxes to East China, respectively; and \(\rho\) is the precipitation recycling ratio (bold numbers indicate that the correlation coefficients have passed the significance test at the 95% confidence level) |
|---|---|---|---|---|---|
| ERA-5 | | | | |
| DJF | 0.54 * | 0.78 | −0.33 | −0.74 |
| MAM | 0.61 * | 0.88 | −0.47 | −0.85 |
| JJA | 0.23 | −0.06 | 0.58 | −0.20 | −0.43 |
| SON | 0.21 | −0.32 | 0.39 | −0.13 | −0.22 |
| CRA-40 | | | | |
| DJF | 0.47 * | 0.74 | −0.32 | −0.71 |
| MAM | 0.43 * | 0.81 | −0.54 | −0.75 |
| JJA | −0.13 | 0.15 | 0.39 | −0.04 | −0.31 |
| SON | 0.17 | −0.23 | 0.36 | −0.26 | −0.08 |

Fig. 9. Temporal evolution of annual mean total precipitation anomaly (black line; \(P\)), precipitation anomalies induced by northern moisture influx (purple line; \(P_N\)), southern moisture influx (blue line; \(P_S\)), eastern moisture influx (red line; \(P_E\)), and western moisture influx (green line; \(P_W\)) relative to 1979–2018 over East China, as derived from (a) ERA-5 and (b) CRA-40 (mm day\(^{-1}\)).
annual moisture flux convergence is approximately 180 mm smaller. The atmospheric water vapor conservation over East China in CRA-40 is reasonable and comparable with that of ERA-5.

(2) CRA-40 well captures the climate mean hydrological cycle characteristics over East China. The mean precipitation over East China is dominated by remote moisture transport. The western moisture influx dominates the precipitation from October to April, and the southern influx is the major contributor in JJA. The southern influx contributes most to annual total precipitation (about 40%), followed by western influx (about 32%). The western moisture influx induced precipitation in CRA-40 is 80 mm less than that in ERA-5. The mean annual precipitation recycling ratio in CRA-40 is 20.1%, which is 1% larger than that in ERA-5. The difference between the two datasets is greater in summer, reaching 4.16%. The more summer precipitation in CRA-40 than ERA-5 mainly comes from more contribution of local evaporation. The maximum difference of each hydrological component between the two datasets appears in summer ($3.57 \times 10^7$ kg s$^{-1}$) and winter runoff ($1.84 \times 10^7$ kg s$^{-1}$).

(3) CRA-40 shows its strength in representing the interannual variability of precipitation averaged over East China. The correlation coefficient of CRA-40 precipitation with observation for 1979–2018 is 0.77, which is much higher than that of ERA-5 (0.33). This is mainly because CRA-40 well captures the positive precipitation anomalies since 2011, due to the positive anomalies of southern influx induced precipitation in CRA-40. Both datasets show that remote moisture influx dominates the precipitation interannual variability. From seasonal aspect, the southern moisture influx plays the most important role in precipitation interannual variability throughout the year, though it is only the major contributor to mean precipitation in JJA. This indicates that the main source of water vapor for mean precipitation is not necessarily the major contributor to precipitation variability over East China. The southern moisture influx shows the highest correlation (0.71) with annual total precipitation in CRA-40, while it is the western influx (0.80) in ERA-5. The contribution of northern influx is greater than that of western influx in CRA-40 during MAM, contrary to ERA-5. These may lead to the difference in precipitation interannual variability between the two datasets.

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