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Moisture Transport versus Precipitation Change in Sub-Basins of the Yangtze River Basin

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Abstract: The Yangtze River Basin (YRB) exhibits great climate heterogeneity, from high-elevated source areas dominated by westerlies to downstream wetlands sensitive to monsoon flows. However, the atmospheric hydrological cycle and associated precipitation changes are rarely being synthetically studied in different sub-basins of the YRB, which are particularly important since floods in the main stream largely result from the superposition of precipitation-runoff peaks from different sub-basins. By dividing the entire YRB into 12 sub-basins, this study presents a preliminary analysis of precipitation features and the associated moisture transport characteristics at the sub-basin scale during 1961–2015. Results suggest that the peak month of precipitation in the northwest sub-basins (July) is one month later than that in the southeast sub-basins (June). The highest total column water vapor (TCWV) contributes to the peak precipitation in July in the northwest sub-basins, while the peak precipitation in June in the southeast sub-basins is more relative to the interaction among multi-circulations (featured by relatively high westerly moisture transport and relatively low south monsoon contribution in the progression process of monsoon precipitation belt). The south monsoon moisture during summer seldom reaches the source region basin (SRB), the Jinshajiang River Basin (JRB), and the Minuoqiang River Basin (MTB). During 1961–2015, the precipitation mainly exhibits an “increase–decrease–increase” pattern from the source region to downstream; however, it is unlikely that this pattern is forced by the TCWV and zonal/meridional moisture transport. In addition, the moisture transport anomalies between wet and dry years are also defined in the 12 sub-basins, and these anomalies are characterized by significantly different moisture transport patterns.

Keywords: Yangtze River Basin; precipitation change; moisture transport; total column water vapor; wet and dry years

1. Introduction

The Yangtze River Basin (YRB) spans three distinct terrain levels of China, originating from the high-altitude Tibetan Plateau, across the Hengduan Mountains, the Yunnan–Guizhou Plateau, the Sichuan Basin, and the Southern Yangtze River Hills, to the fertile wetlands of the Middle-Lower Yangtze River Plain (Figure 1). The YRB covers nearly 1,800,000 km², with its water resources supplying approximately one-third of China’s population and maintaining great contribution to regional agricultural and economic development [1,2], and its hydropower endowment accounts for almost half of the technically exploitable hydroelectricity in the country and ranks number one in the world [3]. The history of YRB is littered with catastrophic flooding events that have caused enormous losses of life and properties [4,5]; thus, a large number of water conservancy projects
(including the Three Gorges Dam) have been constructed in the past several decades [6]. However, YRB continues to be at high risk of flooding and droughts during recently intensified global hydrologic cycles as well as changes in land cover in the region (e.g., the whole-basin floods in 1998 and 2020, and droughts in 1978 and 2011) [4,7–9]. These lead to an increasing number of studies addressing precipitation changes in the YRB, as well as in-depth explorations of the underlying mechanisms of atmospheric circulation [10–14].

Precipitation changes and associated floods and droughts are closely linked to the transport of atmospheric moisture, which supplies continuous precipitable water to a target region [15–18]. Researchers have indicated that most of the terrestrial heavy precipitation and relevant flooding, especially in coastal and mid-latitude areas, is strongly related to intense horizontal moisture transport [19–22]. More interestingly, moisture fluxes have been demonstrated to have even a higher predictability potential than precipitation in predicting seasonal flood events over the YRB [23], since the atmospheric moisture flux is supposed to be better predicted by commonly used global climate models than precipitation [24,25]. In general, moisture contributes to precipitation change over the YRB is affected by circulation systems with different spatial and temporal scales, for example, the East Asian monsoon, the Indian summer monsoon, and the mid-latitude westerlies, as well as their major components such as the western Pacific subtropical high (WPSH), the South Asian high, the East Asian westerly jet, etc. [11,18,26–32]. Under these backgrounds, two major channels conveying moisture to summer precipitation over the YRB have been defined by Xu et al. [32]: one comes from Somalia, crossing the Indian Ocean and the southeast Tibetan Plateau, to the target area, while the other, from the Philippine Sea, passes through the South China Sea and South China, arriving at the YRB. The two moisture flows turn together toward the middle-to-lower reaches of the basin, forming

Figure 1. Topography of the Yangtze River Basin (YRB), with the 12 sub-basins are divided by solid black lines. The 12 sub-basins from source to downstream are source region basin (SRB), Jinshajiang River Basin (JRB), Mintuojiang River Basin (MTB), Wujiang River Basin (WJB), upper mainstream basin (UMB), Jialingjiang River Basin (JLB), Dongtinghu Lake Basin (DTB), middle mainstream basin (MMB), Hanjiang River Basin (HJB), Poyanghu Lake Basin (PYB), lower mainstream basin (LMB), and Taihu Lake Basin (THB). The subplots surrounding the YRB are monthly precipitation patterns for each sub-basins, by using the CMA dataset for the 1961–2015 average (the green, red, yellow, and blue bars represent spring, summer, autumn, and winter precipitation, respectively).
a “large triangle” area as a key region of moisture source of the YRB [32–34]. Of more concern is the heavy precipitation over the YRB, when the atmospheric circulation pattern is characterized by a northwestward extension of WPSH and a southward shift of the East Asian westerly jet (EAJ). These produce a mass of low-latitude oceanic moisture transport to the YRB; by contrast, in dry years, a weak WPSH and a northward displacement of EAJ are usually accompanied by the moisture convergence zone displaces to the north of the YRB [12,28,35–37]. In addition, the invasion of north cold air mass and the largely variational westerlies may also promote the formation of a convergence zone over the YRB by blocking the northward movement of monsoon flows [38–40].

The record-breaking Meiyu (a persistent, nearly stationary weak baroclinic zone in the lower troposphere) in 2020 over the YRB has led to a new upsurge of research studies on the driving mechanisms of extreme precipitation in the region. Different from the cases in 1998 and 2016 featured by a super El Niño, persistent warming in the tropical Indian Ocean, which can be traced back to the super Indian Ocean Dipole (IOD) in 2019, was considered to be another important external contributor that triggered an abundance of low latitude moisture transport to the YRB in 2020 [41–43]. The North Atlantic Oscillation (NAO) phase change was also recognized as being responsible for the change between the warm and cold front stages of Meiyu precipitation in 2020 [44]. In general, the increase in global surface temperature will firstly improve the water capacity of the air and, thus, the potential for more moisture transport to the YRB; furthermore, a large sensible heat flux over the subtropical zone is conducive to the strength of the WPSH with a westward extension, which, in turn, facilitates the persistence of the quasi-stationary front in the YRB during the Meiyu season [35].

However, the YRB contains a multi-terraced terrain and a large climate heterogeneity, from the westernmost high-latitude, cold, and dry source areas dominated by westerly winds and melting water from glacier and snow, to the downstream warm and wet coastal plain areas dominated by East Asia summer monsoon [45,46]. The annual precipitation ranges from 859 mm in the source region to about 1528 mm in the lower reaches [1], and the trends in mean and extreme precipitation have shown great spatial variability among the different sub-basins of the YRB during recent decades [8,47,48]. Moreover, previous studies on moisture transport to the YRB primarily address a study area defined by mean/extreme precipitation events (usually a rectangular area), or focusing on a single basin (e.g., the entire mid-lower reaches or the YRB) [23,27,30,31,33,35,49–52]. Hydrological conditions in tributaries or among different sub-basins are of great concern for water resource management, flood/drought regulation, and relevant policy formulation in the YRB. Beyond the intensity, duration, and total amount of precipitation, flood risks over the YRB are primarily associated with the rain belt migration and the occurrence of strong regional convective weather [9,41]. Of particular concern is the stacking of precipitation-runoff peaks from different sub-basins, which is one of the most important elements that cause severe flooding in the main stream.

All these factors highlight the need for an integrated examination of atmospheric driving factors to precipitation change in different sub-basins of the YRB, which will help to better understand the uneven hydrology patterns over the YRB with diversified landforms and multiple climate systems. This study aims to fill this gap by dividing the entire YRB into 12 sub-basins (Figure 1) and conducting a preliminary analysis of precipitation characteristics, as well as the associated background of moisture transport, in these regions during the period 1961–2015. The main objectives are to (1) characterize the climatological precipitation patterns in the 12 sub-basins of the YRB; (2) explore correlations between moisture transport and precipitation change on the sub-basin scale; (3) detect moisture transport anomalies between wet and dry years in the sub-basins.

2. Materials and Methods

Precipitation used in this study is a high-quality precipitation dataset interpolated from about 2400 meteorological stations over China, initiated by the China Meteorological
Administration (CMA) [53]. This dataset is 0.5° × 0.5° gridded with a time span from 1961 to the present and is dependent on digital elevations by using a thin-plate spline interpolation method with a three-dimensional scheme (http://data.cma.cn, last access: 15 March 2021).

Three latest-generation extended reanalysis products were used to diagnose moisture transport over the YRB, with three variables of total column water vapor (TCWV, mm), vertically integrated northward moisture flux (kg m⁻¹ s⁻¹), and vertically integrated eastward moisture flux (kg m⁻¹ s⁻¹). The three reanalysis products were the fifth generation of atmospheric reanalysis produced by the European Center for Medium-Range Weather Forecasts (ECMWF) (ERA5) [54,55], the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) [56], and the Japanese 55-year Reanalysis (JRA-55) from the Japan Meteorological Agency (JMA) [57]. Table 1 summarizes the basic information of all of the selected datasets. Only monthly temporal resolution was taken into account in this research, and all selected variables were resampled from their original resolution to 0.5° × 0.5° grids to match the CMA precipitation. It is worth noting that all the time spans end in 2015 in this study, due to some missing values in CMA precipitation after 2015.

The ordinary least squares regression method was used to calculate trends, and the relationships between different time series were evaluated using the Pearson correlation coefficient. The relevant statistical significance was estimated by using the two-tailed student’s t-test.

Table 1. Basic information of datasets used in this study.

| Dataset   | Spatial Resolution | Time Span   | Variable                                      |
|-----------|--------------------|-------------|-----------------------------------------------|
| CMA       | 0.5° × 0.5°        | 1961–present| Precipitation                                 |
| ERA5      | 0.25° × 0.25°      | 1950–present| TCWV, vertically integrated northward and eastward moisture flux |
| MERRA-2   | (1/3)° × (2/3)°    | 1980–present|                                             |
| JRA-55    | 0.56° × 0.56°      | 1958–present|                                             |

3. Results

3.1. Precipitation and Moisture Transport Characteristics in Sub-Basins of the YRB

As shown in Figure 1, precipitation amount (1961–2015) in the YRB increases gradually from the northwest source areas to the southeast downstream, almost in all seasons. The lowest annual precipitation occurs in the SRB (441.61 mm), with its precipitation in spring, summer, autumn, and winter at 69.89 mm, 277.90 mm, 84.91 mm, and 8.91 mm, respectively. The highest annual precipitation appears in the PYB (1615.58 mm), about four times that in the SRB, and its precipitation amounts in the four seasons are 621.06 mm, 549.34 mm, 220.05 mm, and 225.13 mm, respectively. Precipitation concentrated in summer in nearly all of the sub-basins (except for the PYB); however, the proportion of summer precipitation decreased from the highest 62.93% in the SRB to only 34.00% in the PYB. Keep consistent with the precipitation amount, the mean annual TCWV also increases from only 4.29 mm in the SRB to 33.12 mm in the PYB, with the highest TCWV occurring in summer in all sub-basins. It should be noted that of all the studied sub-basins, only the PYB shows the highest seasonal precipitation in spring. This may relate to its location, which is more prone to the northwestern advance of East Asia summer monsoon and the influence from WPSH [11]. As also indicated by the northward/eastward moisture fluxes in Figure 2 and the spatial patterns of moisture flux in Figure 3, more moisture can be transported to the most southeast part of the YRB (i.e., the PYB) in spring in comparison with the other sub-basins.
Figure 2. Seasonal cycles of total column water vapor (TCWV, the left axis) and vertically integrated northward/eastward moisture flux (the right axis) in 12 sub-basins over the YRB, by using ERA5 for 1961–2015 average.

At the monthly scale, peak precipitation mainly occurs in July in the northwest sub-basins (i.e., SRB, JSB, MTB, UMB, JLB, HJB, and MMB), but one month ahead (in June) in the southeast sub-basins (i.e., WJB, DTB, PYB, LMB, and THB). The different precipitation peaks do not remain the same with TCWV whose peaks only in July in all of the sub-basins. Firstly, an adequate amount of moisture supply is only one element in precipitation formation, whereas a favorable convection system could be more important. In addition, the summer monsoon precipitation belt presents a progression process from southeast to northwest in East Asia [11], this may strongly link to the displacement of monthly precipitation peaks in different sub-basins of the YRB.

In addition to reflecting moisture transport intensity and transport channels, the seasonal cycles of northward and eastward moisture fluxes in the 12 sub-basins in Figure 2 are also beneficial in reflecting the interactions among different large scale circulation systems, for instance, the East Asia monsoon, the Indian monsoon, the mid-latitude westerlies, as well as the WPSH and EAJ. Figure 3 displays the spatial patterns of moisture flux over the YRB region from January to December. In winter, the entire YRB is dominated by eastward moisture flux (mainly the mid-latitude westerlies), with the moisture transport in the southeast part being significantly higher than that in the northwest part. In spring, moisture fluxes from the southwest gradually increase over the southeast part of the YRB. However, the most northwest part (i.e., the SRB, JSB, and MTB) is still controlled by eastward moisture fluxes. In summer, the outbreaking of East Asia and Indian monsoon systems bring a large amount of oceanic moisture toward the middle-to-lower reaches of the YRB, and this
process is accompanied by a reduction in eastward moisture flux in all of the sub-basins (Figure 2). Especially in July, the northward moisture transport peaks in all middle-to-lower reaches except for the most northwest part of the YRB (i.e., SRB, JSB, and MTB), where the variation of northward moisture flux is relatively stable during the year. This indicates that, of all of the sub-basins in the YRB, the SRB, JSB, and MTB are relatively weakly influenced by summer monsoon systems. In contrast, the eastward moisture transport reaches an annual minimum in August in all of the sub-basins (Figure 2). This may be influenced by the northward shift of the westerlies and weaken wind speed during this period [58]. In autumn, the eastward moisture transport recovery gradually with the retreat of monsoon systems. It is worth noting that, from August to September, all of the western sub-basins exhibit slight increases in northward and eastward moisture transport simultaneously, while in the eastern sub-basins, the northward moisture transports all decrease (Figure 2). In September, the eastern YRB even forms an “anticyclone” pattern of moisture flux, with its center on the DTB and PYB (Figure 3). This brings intensified moisture fluxes in the south part of the Sichuan Basin, which may trigger increased precipitation from August to September in the JLB.

3.2. Changes in Precipitation and Moisture Transport in Sub-Basins of the YRB

Precipitation trends during 1961–2015 over the YRB are displayed in Figure 4a, in which the wetting trends mainly appear in the source areas and downstream of the YRB. The sub-basins with significantly increased precipitation (p < 0.05) are the westernmost SRB (1.66 mm year\(^{-1}\)) and the easternmost THB (3.38 mm year\(^{-1}\)). Several areas in the central YRB, particularly neighboring the west and east parts of the Sichuan Basin, exhibit a significant decreasing trend of precipitation. Around these areas, five sub-basins show slightly drying trends (−0.20, −1.33, −1.09, −0.15, and −0.14 mm year\(^{-1}\) in the MTB, WJB, UMB, JLB, and HJB, respectively) but without significance.

The trends of TCWV and northward/eastward moisture fluxes during 1961–2015 are displayed in Figure 4b–d. Over the YRB, both of the trends of TCWV and eastward moisture flux show roughly a similar spatial pattern with the precipitation change, with an “increase–decrease–increase” pattern from the northwest to the southeast. These relation-
ships could also be reflected by the significant correlation coefficients between precipitation and TCWV (0.57) and eastward moisture flux (0.44) over the YRB, while no significant correlation is found between precipitation and northward moisture flux. However, trends in precipitation and TCWV and eastward moisture flux are not strictly consistent across sub-basins, particularly around the western Sichuan Basin and in the easternmost THB and LMB. By contrast, the trend of northward moisture transport presents a unique spatial pattern featured by a distinct discrepancy between the western and eastern parts of the YRB. A pronounced weakening trend of northward moisture fluxes is observed throughout the eastern part of the YRB (roughly in the east of 106° E), which keeps consistent with the weakening East Asia monsoon intensity since the late 1970s [59,60].

![Figure 4](image_url)

**Figure 4.** Trends of precipitation (a), TCWV (b), northward moisture flux (c), and eastward moisture flux (d) over the YRB, by using CMA precipitation and ERA5 during 1961–2015. Stippling indicates regions with statistically significant trends (p < 0.05).

All of the trends in sub-basins are quantified in Table 2, in which significantly increased TCWV is found in the most northwest part (SRB and MTB) and significantly decreased northward moisture flux is found in the north-central sub-basins (MMB and HJB). No significant trends of eastward moisture flux are found in all sub-basins, although there is a visible “increase–decrease–increase” pattern across the whole YRB. To further clarify the relationships between precipitation and moisture transport, the correlation coefficients between precipitation and TCWV, northward moisture flux, and eastward moisture flux in the sub-basins during 1961–2015 were also calculated and are listed in Table 2. The annual variations of TCWV could effectively reflect precipitation changes in different parts of the YRB, with significant correlations between precipitation and TCWV found in all of the sub-basins. On the one hand, precipitation formation depends on an adequate moisture supply. On the other hand, increased precipitation, in turn, provides more water that can be evaporated into the air. Under the interaction among multi-circulations (such as monsoon fluxes, westerlies, and the invasion of north cold air mass) [11], the variation in zonal moisture transport more likely influences annual precipitation change in the middle-to-lower reaches of the YRB, and the meridional moisture transport is more capable of affecting annual precipitation variability in the north-central and northwest sub-basins.
Table 2. Trends of annual precipitation, TCWV, northward moisture flux, and eastward moisture flux, and correlation coefficients between precipitation and TCWV, northward moisture flux, and eastward moisture flux in the YRB and the 12 sub-basins, by using CMA precipitation and ERA5 during 1961–2015.

| Sub-basin | Precipitation (mm year⁻¹) | TCWV (mm year⁻¹) | Northward Moisture Flux (kg m⁻¹ s⁻¹ year⁻¹) | Eastward Moisture Flux (kg m⁻¹ s⁻¹ year⁻¹) | Correlations with Precipitation |
|-----------|--------------------------|-----------------|---------------------------------------------|---------------------------------------------|---------------------------------|
| YRB       | 0.72                     | 0.17 x 10⁻²     | -8.91 x 10⁻²                                | 1.23 x 10⁻²                                 | 0.57*                           |
| SRB       | 1.66*                    | 0.55 x 10⁻²     | 0.26 x 10⁻²                                 | 2.27 x 10⁻²                                 | 0.63*                           |
| JSB       | 0.11                     | 0.23 x 10⁻²     | -0.10 x 10⁻²                                | 3.40 x 10⁻²                                 | 0.48*                           |
| MTB       | -0.20                    | 0.92 x 10⁻²     | -0.70 x 10⁻²                                | 2.17 x 10⁻²                                 | 0.45*                           |
| WJB       | -1.33                    | -0.27 x 10⁻²    | -14.05 x 10⁻²                               | -0.89 x 10⁻²                                | 0.39*                           |
| UMB       | -1.09                    | -0.06 x 10⁻²    | -10.35 x 10⁻²                               | 1.43 x 10⁻²                                 | 0.34*                           |
| JLB       | -0.15                    | 0.50 x 10⁻²     | -4.76 x 10⁻²                                | -1.43 x 10⁻²                                | 0.34*                           |
| DTB       | 1.07                     | -0.05 x 10⁻²    | -20.43 x 10⁻²                               | 0.42 x 10⁻²                                 | 0.54*                           |
| MMB       | 0.81                     | -0.27 x 10⁻²    | -20.73 x 10⁻²                               | -2.94 x 10⁻²                                | 0.52*                           |
| HJB       | -0.14                    | -0.53 x 10⁻²    | -15.86 x 10⁻²                               | -3.13 x 10⁻²                                | 0.55*                           |
| PYB       | 3.64                     | 0.54 x 10⁻²     | -10.59 x 10⁻²                               | 9.02 x 10⁻²                                 | 0.62*                           |
| LMB       | 2.74                     | -0.19 x 10⁻²    | -10.40 x 10⁻²                               | -2.35 x 10⁻²                                | 0.50*                           |
| THB       | 3.38*                    | -0.08 x 10⁻²    | -8.54 x 10⁻²                                | -0.63 x 10⁻²                                | 0.53*                           |

Note: * represent statistically significant trends with $p < 0.05$.

The monthly trends (1961–2015) of precipitation, TCWV, northward/eastward moisture flux in the 12 sub-basins are also illustrated in Figure 5, to further detect links between precipitation change and moisture transport on a seasonal scale. In the westernmost sub-basin (SRB), significant wetting trends concentrate in the first half of a year (from January to June), with the highest wetting trend occurring in June (0.43 mm year⁻¹), when the TCWV and eastward moisture transport both increase significantly. In the easternmost sub-basin (THB), significant wetting trends occur only in January (0.63 mm year⁻¹) and August (1.24 mm year⁻¹). However, there is a sudden shift from a significant wetting trend in August to a significant drying trend in September (~1.03 mm year⁻¹) in the THB; this may indicate a dramatic change of hydrological regime in the region. In the other sub-basins with insignificant precipitation trends on an annual scale, decreased precipitation occurs mainly in April (except for JSB and MTB) and September (except for DTB), and increased precipitation largely appears in summer in most of the middle to lower reaches of the YRB. Actually, given the complexity of driving mechanisms of precipitation change, trend consistencies between precipitation and moisture transport are low in almost all of the sub-basins. Nevertheless, the most pronounced monthly trends of moisture transport are the increasing TCWV in June, when 10 out of the 12 sub-basins show significance, and the northward moisture fluxes mainly show decreasing trends in April, July, and August in most of the middle-to-lower reaches of the YRB. This indicates that the influence of the weakening northward moisture transport (i.e., the monsoon systems) over the YRB is either before the monsoon outbreaking (April) or in the later monsoon season (July and August).

3.3. Moisture Transport between Wet and Dry Years in Sub-Basins of the YRB

In this section, we investigate anomalies of moisture transport between wet and dry years in different sub-basins, in order to suggest basic moisture transport patterns for extreme precipitation periods in different parts of the YRB. The annual time series of precipitation anomalies during 1961–2015 in all of the 12 sub-basins of the YRB are shown in Figure 6, with the respective wettest three years and the driest three years labeled in each subplot. These labeled years were selected as the typical wet and dry years. Precipitation changes in different parts of the YRB exhibit significantly different interannual patterns, with no two sub-basins showing the same distribution of wet and dry years. Accordingly,
the anomalies of moisture flux between wet and dry years (wet–dry) in all 12 sub-basins are illustrated in Figure 7. To quantitatively summarize the different moisture transport patterns in Figure 7, the mean TCWV and mean northward/eastward moisture flux during 1961–2015, in the wet and dry years in the 12 sub-basins were also calculated and are shown in Table S1.

Figure 5. Monthly trends of precipitation (mm year$^{-1}$), TCWV (mm year$^{-1}$), northward moisture flux (kg m$^{-1}$ s$^{-1}$ year$^{-1}$), and eastward moisture flux (kg m$^{-1}$ s$^{-1}$ year$^{-1}$) in 12 sub-basins over the YRB, by using CMA precipitation and ERA5 during 1961–2015. All the positive/negative trends are standardized by dividing $x_{\text{max}} - x_{\text{min}}$, and bars, with black edges representing statistically significant trends ($p < 0.05$).

It is found that the moisture flux anomalies between wet and dry years in the different sub-basins of the YRB have significant differences (Figure 7). In the SRB, an intensified southward moisture transport is found in the eastern part of the YRB. By certain teleconnection processes, the increased monsoon transport from north to south in the eastern YRB may trigger higher precipitation in the high-elevated SRB. Actually, a study has found that humid years in the western part of the SRB were accompanied by negative Southern Oscillation Index (SOI), which is featured by intensified southward moisture flux at 500 mb in east China [61]. In the JSB, increased moisture transports from both the southwest and northeast directions converge on the region and bring abundant precipitation. In the MTB, the easterly wind carries masses of oceanic moisture downstream of the YRB and then turns northward in the middle reaches. The northward moisture transport and westerlies meet roughly in the southeastern part of the MTB. This pattern is similar to that observed in the JLB when sufficient moisture is transported to the JLB from the south. However, unlike the initial moisture source of the MTB from the eastern oceans, the extra moisture that contributes to the wet years of the JLB originates mostly from southern and southeastern areas. In the WJB, increased moisture transport from the southwest and southeast directions converges in the middle-to-lower reaches of the YRB, then turns northwest and
forms a “cyclone” circulation with the convergence zone in the WJB. In the UMB, increased moisture transport is found across the YRB from south to northeast, and meets a branch of intensified moisture transport from the north, forming a convergence zone in the UMB.

Figure 6. Annual time series of precipitation anomalies in the 12 sub-basins of the YRB, by using CMA precipitation during 1961–2015. The representative wet and dry years are labeled in each subplot.

Figure 7. Vertically integrated moisture flux anomalies over the YRB between wet and dry years (wet–dry) in the 12 sub-basins, by using ERA5. The red dots denote the location of each sub-basin.
In the middle-to-lower reaches of the YRB, a most pronounced moisture transport feature during the wet years is the mass of extra moisture transport from the southwest, and the coverage of this intensified moisture flux is mainly located at the southeast part of the YRB (Figure 7). The HJB is different, where both intensified southeast and southwest moisture fluxes affect the middle-to-lower reaches of the YRB. This pattern is similar to that in the JLB but with significantly increased intensity. In the DTB, MMB, PYB, LMB, and THB, pronounced southwest moisture transport encounters with increased moisture transport from the northeast and north directions. Although with different locations and intensities, these moisture fluxes finally form a convergence zone in the respective sub-basins. The intensified monsoon flow from the southwest and the frequent intrusion of north cold air masses are probably the critical modes of moisture transport during wet years in the middle-to-lower reaches of the YRB. Actually, scientists have discovered that the anomalous high precipitation over East Asia was accompanied by circulation anomalies characterized by a typical meridional teleconnection—a significant anticyclonic anomaly in the tropical western North Pacific and a significant cyclonic anomaly in the mid-latitudes of East Asia [11,28,37]. The changes in location and intensity of this teleconnection model likely shape the different moisture transport patterns in different sub-basins of the YRB.

4. Discussion

Uncertainties and systematic bias in reanalysis products have been observed by previous researchers when estimating the hydrological cycle on both regional and global scales, due to the different assimilation systems, input data, and model physics [62–64]. Over the YRB, the selection of different datasets may also affect reliabilities/errors in studying moisture transport to a certain extent. To better understand uncertainties caused by different datasets, three latest-generation extended reanalysis products (ERA5, MERRA-2, and JRA-55) in reflecting moisture transport over the YRB during 1980–2015 are compared in this section. We believe that the selection of multiple reanalysis products, instead of a single dataset, can lead to more credible results in this research.

The multiyear average (1980–2015) TCWV and vertically integrated moisture flux over the YRB by using ERA5, MERRA-2, and JRA-55 are displayed in Figure 8. Except for some slight quantitative differences, there are no apparent spatial discrepancies among the three reanalysis products. The TCWV and moisture flux both show a decreasing pattern from the high-elevated northwest, which is dominated by the mid-latitude westerlies to the southeastern part, which is near the oceans and is susceptible to monsoon flows. The most visible discrepancies among the three datasets are mainly located in the southeastern YRB, where the values of TCWV and moisture flux are relatively higher in ERA5 and MERRA-2 than that in JRA-55. For annual variations, Figure 9 shows the time series of TCWV, vertically integrated northward moisture flux, and vertically integrated eastward moisture flux over the YRB by using ERA5, MERRA-2, and JRA-55 during 1980–2015. In comparison with ERA5 over the entire YRB, the relative biases of TCWV are −1.95% for MERRA-2 and −9.98% for JRA-55; the relative biases of northward moisture flux are 0.15% for MERRA-2 and −26.63% for JRA-55; the relative biases of eastward moisture flux are 7.75% for MERRA-2 and −5.85% for JRA-55. The most significant bias exhibits in the northward moisture flux of JRA-55; however, the annual correlation coefficients among the three datasets for different variables are all significant with p < 0.001. This suggests a high degree of coherence for annual variations among ERA5, MERRA-2, and JRA-55. For annual trends, the decreasing trends of northward and eastward moisture fluxes all keep consistent across the three datasets, although there are some differences in value. The TCWV in MERRA-2 shows an inverse trend with that in ERA5 and JRA-55; however, these trends are relatively small and without significance.
In examining characteristics of Meiyu precipitation in June and July, Tong and Zheng [65] reported that ERA5 and MERRA-2 are more consistent with the Tropical Rainfall Measuring Mission (TRMM) precipitation with respect to mean and variance patterns, while JRA-55 has lower mean precipitation and variance in the middle-to-lower reaches of the YRB. However, the three datasets are all capable of capturing the intensification of relative
humidity, as well as the northward movement of the rain belt (as shown in TRMM) during the Meiyu season [65]. In addition, the precipitation in ERA-Interim (the predecessor product of ERA5) shows a better performance of spatial variation over monsoon Asia than JRA-55, but JRA-55 has a more consistent temporal variation with observations [66,67]. Except for precipitation, there is still a lack of studies on the credibility of moisture transport in ERA5 with other latest-generation reanalysis products over the YRB. However, as discussed in this section, the three datasets generally show good agreement in determining spatial and annual variation characteristics of moisture transport over the YRB. Such consistency further demonstrates the reliability of moisture transport analysis based on ERA5 in this study.

5. Conclusions

Hydrological conditions on a sub-basin scale play an essential role in water resources management, flood–drought regulation, and relevant policy formulation over the YRB. In this study, a preliminary analysis between precipitation and moisture transport was presented in 12 sub-basins of the YRB, based on CMA precipitation and a latest-generation reanalysis product (ERA5) during 1961–2015. We examined in detail the precipitation and moisture transport features, as well as their changes in all of the sub-basins. The moisture transport anomalies between wet and dry years in different sub-basins were also evaluated.

The main conclusions are as follows:

(1) Seasonal precipitation in the southeastern sub-basins (WJB, DTB, PYB, LMB, and THB) peaks in June, but in the northwestern sub-basins (SRB, JSB, MTB, UMB, JLB, HJB, and MMB) peaks in July. This pattern is not strictly consistent with the TCWV, which peaks only in July in all of the sub-basins. In the middle-to-lower reaches of the YRB, the northward moisture transport reaches the highest level in summer and peaks in July. However, the most northwestern sub-basins (SRB, JSB, and MTB) can hardly be influenced by the south monsoon moisture. With the zonal shift in precipitation belt during the monsoon season, the precipitation peaks in July in southeastern sub-basins. This is also featured by relatively high westerly moisture transport and relatively low south monsoon contribution.

(2) During 1961–2015, trend consistencies between precipitation and TCWV and northward/eastward moisture fluxes are weak in most of the sub-basins. However, all sub-basins show an increasing TCWV in June, with 10 of the 12 sub-basins being significant. In terms of annual variation during 1961–2015, the zonal moisture transport has a significant impact on precipitation changes in the middle-to-lower reaches of the YRB, while the meridional moisture transport mainly affects precipitation variations in the north-central and northwest sub-basins.

(3) The moisture transport anomalies between wet and dry years are significantly different in different sub-basins of the YRB. For instance, there is a teleconnection between wet years in the SRB and intensified southward moisture transport in the eastern part of the YRB. The wet years in the north-central sub-basins (MTB, JLB, and HJB) are mainly accompanied by an increased northward moisture transport over the mid-eastern YRB. In the middle-to-lower reaches of the YRB, changes in the location of convective zones, which are caused by frequent encounters of intensified monsoon, flow from the southwest, and cold air masses from the north, bringing wet years in the different sub-basins.

This study focused mainly on moisture transport over the YRB region, and only a simple profile was presented at the present stage. A future in-depth study is expected to consider more detailed weather dynamical processes and expand the spatial scale to reflect more configurations of large-scale circulation systems, such as the WPSH, the EAJ, the NAO, and the sea surface temperature anomaly between Indian and East Pacific Oceans. In addition, based on numerical moisture tracking and regional climate models, a more accurate evaluation of the moisture transport process based on precipitation changes in different sub-basins of the YRB is also valuable to further investigate.
Supplementary Materials: The following supporting information can be downloaded at: [https://www.mdpi.com/article/10.3390/w14040622/s1](https://www.mdpi.com/article/10.3390/w14040622/s1); Table S1: The mean TCWV (mm) and mean Northward/Eastward moisture flux (kg m\(^{-1}\) s\(^{-1}\)) during 1961–2015 and in the wet and dry years in the twelve sub-basins of the YRB, by using ERA5.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

| Abbreviation | Full Form |
|--------------|-----------|
| YRB          | Yangtze River Basin |
| SRB          | source region basin |
| JRB          | Jinshajiang River Basin |
| MTB          | Mintuojiang River Basin |
| WJB          | Wujiang River Basin |
| UMB          | upper mainstream basin |
| JLB          | Jialingjiang River Basin |
| DTB          | Dongtinghu Lake Basin |
| MMB          | middle mainstream basin |
| HJB          | Hanjiang River Basin |
| PYB          | Poyanghu Lake Basin |
| LMB          | lower mainstream basin |
| THB          | Taihu Lake Basin |
| WPSh         | Western Pacific subtropical high |
| EAJ          | East Asian westerly jet |
| IOD          | Indian Ocean Dipole |
| NAO          | North Atlantic Oscillation |
| SOI          | Southern Oscillation Index |
| CMA          | China Meteorological Administration |
| ECMWF        | European Centre for Medium-Range Weather Forecasts |
| ERA5         | the fifth generation of atmospheric reanalysis produced by the ECMWF |
| NASA         | National Aeronautics and Space Administration |
| MERRA-2      | Modern-Era Retrospective Analysis for Research and Applications version 2 |
| JRA-55       | Japanese 55-year Reanalysis |
| JMA          | Japan Meteorological Agency |
| TRMM         | Tropical Rainfall Measuring Mission |
| ERA-Interim  | ECMWF interim reanalysis |
29. Li, X.-F.; Li, J.; Li, Y. Recent Winter Precipitation Increase in the Middle–Lower Yangtze River Valley since the Late 1970s: A Response to Warming in the Tropical Indian Ocean. *J. Clim.* 2015, 28, 3857–3879. [CrossRef]

30. Fremme, A.; Sodemann, H. The role of land and ocean evaporation on the variability of precipitation in the Yangtze River valley. *Hydrol. Earth Syst. Sci.* 2019, 23, 2525–2540. [CrossRef]

31. Wei, J.; Dirmeyer, P.A.; Bosilovich, M.G.; Wu, R. Water vapor sources for Yangtze River Valley rainfall: Climatology, variability, and implications for rainfall forecasting. *J. Geophys. Res. Atmos.* 2012, 117, 214–221.

32. Xu, X.; Chen, L.; Wang, X.; Miao, Q.; Tao, S. Moisture transport source/sink structure of the Meiyu rain belt along the Yangtze River valley. *Chin. Sci. Bull.* 2004, 49, 181. [CrossRef]

33. Xu, X.D.; Shi, X.Y.; Wang, Y.Q.; Peng, S.Q.; Shi, X.H. Data analysis and numerical simulation of moisture source and transport associated with summer precipitation in the Yangtze River Valley over China. *Meteorol. Atmos. Phys.* 2008, 100, 217–231. [CrossRef]

34. Xu, X.; Miao, Q.; Wang, J.; Zhang, X. The water vapor transport model at the regional boundary during the Meiyu period. *Adv. Atmos. Sci.* 2003, 20, 333–342. [CrossRef]

35. Gao, T.; Xie, L.; Liu, B. Association of extreme precipitation over the Yangtze River Basin with global air-sea heat fluxes and moisture transport. *Int. J. Climatol.* 2016, 36, 3020–3038.

36. Zhou, J.; Zuo, Z.; Rong, X. Comparison of the effects of soil moisture and El Nino on summer precipitation in eastern China. *Sci. China-Earth Sci.* 2020, 63, 267–278. [CrossRef]

37. Li, C.; Lu, R.; Li, G. Different Configurations of Interannual Variability of the Western North Pacific Subtropical High and East Asian Westernly Jet in Summer. *Adv. Atmos. Sci.* 2021, 38, 931–942.

38. Hu, Y.; Deng, Y.; Zhou, Z.; Cui, C.; Dong, X. A statistical and dynamical characterization of large-scale circulation patterns associated with summer extreme precipitation over the middle reaches of Yangtze river. *Climate Dyn.* 2019, 52, 6213–6228.

39. Wang, S.; Zuo, H.; Zhao, S.; Zhang, J.; Lu, S. How East Asian westerly jet’s meridional position affects the summer rainfall in Yangtze-Huaihe River Valley? *Clim. Dyn.* 2018, 51, 4019–4121.

40. Wang, S.; Zuo, H.; Zhao, S.; Zhang, J.; Lu, S. How East Asian westerly jet’s meridional position affects the summer rainfall in Yangtze-Huaihe River Valley? *Clim. Dyn.* 2018, 51, 4019–4121.

41. Ding, Y.; Liu, Y.; Hu, Z.Z. The Record-breaking Meiyu in 2020 and Associated Atmospheric Circulation and Tropical SST Anomalies. *Adv. Atmos. Sci.* 2021, 38, 1980–1993.

42. Takaya, Y.; Ishikawa, I.; Kobayashi, C.; Endo, H.; Ose, T. Enhanced Meiyu-Baiu Rainfall in Early Summer 2020: Aftermath of the Subseasonal Phase Transition of the North Atlantic Oscillation. *Geophys. Res. Lett.* 2021, 48, e2020GL090571. [CrossRef]

43. Zhou, Z.-Q.; Xie, S.-P.; Zhang, R. Historic Yangtze flooding of 2020 tied to extreme Indian Ocean conditions. *Proc. Natl. Acad. Sci. USA* 2021, 118, e2022255118. [CrossRef]

44. Liu, B.; Yan, Y.; Zhi, C.; Ma, S.; Li, J. Record-Breaking Meiyu Rainfall Around the Yangtze River in 2020 Regulated by the Subseasonal Phase Transition of the North Atlantic Oscillation. *Geophys. Res. Lett.* 2020, 47, e2020GL090342. [CrossRef]

45. Wang, W.; Lin, H.; Chen, N.; Chen, Z. Evaluation of multi-source precipitation products over the Yangtze River Basin. *Atmos. Res.* 2021, 249, 105287. [CrossRef]

46. Becker, S.; Gemmer, M.; Jiang, T. Spatiotemporal analysis of precipitation trends in the Yangtze River catchment. *Stoch. Environ. Res. Risk Assess.* 2006, 20, 435–444.

47. Li, X.; Zhang, K.; Gu, P.; Feng, H.; Yin, Y.; Chen, W.; Cheng, B. Changes in precipitation extremes in the Yangtze River Basin during 1960-2019 and the association with global warming, ENSO, and local effects. *Sci. Total Environ.* 2021, 760, 144244.

48. Li, Y.; Yan, D.; Peng, H.; Xiao, S. Evaluation of precipitation in CMIP6 over the Yangtze River Basin. *Atmos. Res.* 2021, 253, 105406.

49. Zeng, L.; Schmitt, R.W.; Li, L.; Wang, Q.; Wang, D. Forecast of summer precipitation in the Yangtze River Valley based on South China Sea springtime sea surface salinity. *Clim. Dyn.* 2019, 53, 5495–5509.

50. Wang, N.; Zeng, X.-M.; Guo, W.-D.; Chen, C.; You, W.; Zheng, Y.; Zhu, J. Quantitative diagnosis of moisture sources and transport pathways for summer precipitation over the mid-lower Yangtze River Basin. *J. Hydrol.* 2018, 559, 252–265.

51. Leung, M.Y.T.; Qiu, S.; Zhou, W. Modulations of rising motion and moisture on summer precipitation over the middle and lower reaches of the Yangtze river. *Clim. Dyn.* 2018, 51, 4259–4269.

52. Chen, B.; Zhang, W.; Yang, S.; Xu, X.D. Roles of oceanic moisture exports in modulating summer rainfall over the middle-lower Yangtze River Basin: Inter-annual variability and decadal transition. *Int. J. Climatol.* 2020, 40, 3757–3770. [CrossRef]

53. Zhao, Y.; Zhu, J.; Xu, Y. Establishment and assessment of the grid precipitation datasets in China for recent 50 years. *J. Meteorol. Sci.* 2014, 34, 414–420.

54. Hersbach, H.; Bell, B.; Berrisford, P.; Biavati, G.; Horányi, A.; Muñoz Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Rozum, I.; et al. ERA5 monthly averaged data on single levels from 1979 to present. *Copern. Clim. Change Serv. (C3S) Clim. Data Store (CDS)* 2019, 10, 252–266.

55. Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Munoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* 2020, 146, 1999–2049. [CrossRef]

56. Gelaro, R.; McCarty, W.; Suárez, M.J.; Todling, R.; Molod, A.; Takacs, L.; Randles, C.A.; Darmenov, A.; Bosilovich, M.G.; Reichle, R. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *J. Climate* 2017, 30, 5419–5454.
57. Kobayashi, S.; Ota, Y.; Harada, Y.; Ebita, A.; Moriya, M.; Onoda, H.; Onogi, K.; Kamahori, H.; Kobayashi, C.; Endo, H. The JRA-55 reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan* 2015, 93, 5–48.

58. Jiang, Y.; Luo, Y.; Zhao, Z.; Tao, S. Changes in wind speed over China during 1956–2004. *Theor. Appl. Climatol.* 2010, 99, 421–430. [CrossRef]

59. Chen, W.; Wang, L.; Feng, J.; Wen, Z.; Wang, C. Recent Progress in Studies of the Variabilities and Mechanisms of the East Asian Monsoon in a Changing Climate. *Adv. Atmos. Sci.* 2019, 36, 887–901.

60. Zhou, T.; Gong, D.; Li, J.; Li, B. Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon—Recent progress and state of affairs. *Meteorologische Zeitschrift* 2009, 18, 455–467. [CrossRef]

61. Du, Y.; Berndtsson, R.; An, D.; Zhang, L.; Yuan, F.; Hao, Z. Integrated large-scale circulation impact on rainy season precipitation in the source region of the Yangtze River. *Int. J. Climatol.* 2019, 40, 2285–2295. [CrossRef]

62. Bosilovich, M.G.; Robertson, F.R.; Takacs, L.; Molod, A.; Mocko, D. Atmospheric water balance and variability in the MERRA-2 reanalysis. *J. Clim.* 2017, 30, 1177–1196. [CrossRef]

63. Trenberth, K.E.; Fasullo, J.T.; Mackaro, J. Atmospheric Moisture Transports from Ocean to Land and Global Energy Flows in Reanalyses. *J. Clim.* 2011, 24, 4907–4924.

64. Robertson, F.R.; Bosilovich, M.G.; Roberts, J.B. Reconciling land–ocean moisture transport variability in reanalyses with P–ET in observationally driven land surface models. *J. Clim.* 2016, 29, 8625–8646. [PubMed]

65. Tong, M.; Zheng, Z.; Fu, Q. Characteristics of Meiyu Seen from Multiple Observational Analyses and Reanalyses. *Earth Space Sci.* 2021, 8, e2021EA001647. [CrossRef]

66. Ceglar, A.; Toreti, A.; Balsamo, G.; Kobayashi, S. Precipitation over Monsoon Asia: A Comparison of Reanalyses and Observations. *J. Clim.* 2017, 30, 465–476. [CrossRef]

67. Chen, G.X.; Iwasaki, T.; Qin, H.L.; Sha, W.M. Evaluation of the Warm-Season Diurnal Variability over East Asia in Recent Reanalyses JRA-55, ERA-Interim, NCEP CFSR, and NASA MERRA. *J. Clim.* 2014, 27, 5517–5537. [CrossRef]