ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 30, NO. 6, 2013, 1653–1662

Development of a Meteorological and Hydrological Coupling Index for Droughts and Floods along the Yangtze River Valley of China

NIU Tao[1] (牛 涛), WANG Jizhi*[1] (王继志), YANG Yuanqin[1] (杨元琴), LIU Hongli[1] (刘洪利),
CHEN Miao[3] (陈 淼), and LIU Jiyan[2] (刘冀彦)

[1] *Chinese Academy of Meteorological Sciences, Beijing* 100081

[2] *Yunnan University, Kunming* 65009

[3] *Nanjing University of Information Science and Technology, Nanjing* 210044

(Received 6 December 2012; revised 3 March 2013; accepted 4 March 2013)

ABSTRACT

To comprehensively investigate characteristics of summer droughts and floods in the Yangtze River valley, a meteorological and hydrological coupling index (MHCI) was developed using meteorological and hydrological data. The results indicate that: (1) in representing drought/flood information for the Yangtze River valley, the MHCI can reflect composite features of precipitation and hydrological observations; (2) comprehensive analysis of the interannual phase difference of the precipitation and hydrological indices is important to recognize and predict annual drought/flood events along the valley; the hydrological index contributes more strongly to nonlinear and continuity features that indicate transition from long-term drought to flood conditions; (3) time series of the MHCI from 1960–2009 are very effective and sensitive in reflecting annual drought/flood characteristics, i.e. there is more rainfall or typical flooding in the valley when the MHCI is positive, and vice versa; and (4) verification of the MHCI indicates that there is significant correlation between precipitation and hydrologic responses in the valley during summer; the correlation coefficient was found to reach 0.82, exceeding the 0.001 significance level.

Key words: meteorological and hydrological coupling index (MHCI), Yangtze River valley, recent 50 years, drought and flood

Citation: Niu, T., J. Z. Wang, Y. Q. Yang, H. L. Liu, M. Chen, and J. Y. Liu, 2013: Development of a meteorological and hydrological coupling index for droughts and floods along the Yangtze River valley of China. *Adv. Atmos. Sci.*, **30**(6), 1653–1662, doi: 10.1007/s00376-013-2303-0.

1. Introduction

As a large-scale rain belt over East Asia, the mei-yu frontal system extends from the Yangtze River and Huaihe River valleys eastward to the Korean Peninsula and islands of Japan, and is closely linked to the summer monsoon. Previous studies have pointed out that the intensity of the mei-yu front in China has significant correlation with the summer monsoon circulation over East Asia, and summer rainfall intensity in the latter region is one of the major characteristics of the East Asian monsoon (Wang and Li, 1982; Wang and Leftwich, 1984; Lü et al., 2006; Li and Qu, 2000). A weak East Asian monsoon is usually associated with a strong mei-yu front. During the period from June to August, the mei-yu frontal system swings slightly north and south, mainly over the Yangtze River valley of China, and then moves east to Japan. The mei-yu front is a principal component of the East Asian monsoon (Lü et al., 2006) and is an important research topic in the study of that monsoon (Zhang, 2006). The Yangtze River valley is hydrographically very broad, encompassing a large number of watersheds and tributaries, and the intensity of the mei-yu front in this region can basically describe the main trends of summer drought and flooding in China. Therefore, studying the correlation between the monsoon and the Yangtze River mei-yu has been a focus of scientists both nationally and internationally for some time. The primary problem, in terms of the relation-

---

*Corresponding author: WANG Jizhi, wjz@cams.cma.gov.cn ship between the monsoon and drought or flooding in this river valley, has been how to improve the accuracy and objectivity in analysis and assessment of interannual rainfall intensity. Discussion of this problem is conducive to further improving the recognition of interannual variations (Ping and Luo, 2006).

A reasonable analysis and assessment of mei-yu intensity in the Yangtze valley can directly contribute to the interpretation of monsoon impact mechanisms. In fact, many researchers have already achieved much in this respect (Chang and Chen, 1995; Matsumoto, 1997; Lin and Wang, 2002; Xu et al., 2004). However, owing to the use of dissimilar datasets, as well as the focus of each study having been different, the findings of these works have been varied (Ma, 2003), and even conflicting at times. In their research on the interannual variation of precipitation intensity over the Yangtze River valley, Wang et al. (2008) focused on the lower reaches of the river, using surface observations of 78 stations in Anhui Province during 1961–2005. They found that precipitation intensity in the mei-yu season was strong in the 1960s, weak in the 1970s, strong again in the 1980s, and has essentially been normal since the 1990s. Zhang et al. (2007) analyzed monthly rainfall data from Changsha Station during 1951–2005, revealing that precipitation there clearly increased during the last half-century, at a rate of 59.6 mm $(10\ \mathrm{yr})^{-1}$. Wang (2004) selected and studied observation data from the upper reaches of the Yangtze River during 1950–90 from representative stations, concluding that precipitation intensity from 1960–99 declined at a rate of -6.6 mm $(10\ \mathrm{yr})^{-1}$.

To assess annual intensity of monsoon rainfall, researchers have achieved a great deal in developing indices that depict annual precipitation, flood and drought situations. In fact, the trend in annual drought and flooding has emerged to be of major importance in many disciplines. Standards for defining droughts and floods vary, and these differences currently represent a restriction in terms of their study. Accordingly, many studies have been conducted to attempt to define drought/flood indices. For instance, a "Z index" of regional drought and flooding was put forward by Tan et al. (2002). To obtain this index, the Z-coordinate of precipitation amount is transformed in order to make the time series approximate a normal distribution, and then droughts and floods can be classified. Further studies have shown that the Z index for a single station is superior to other indices (Gao et al., 1998). The latter authors ascertained severe drought/flood years in the southern Jiangnan region and northern South China using the Z index. Essentially, there are two types of regional drought/flood index. One classifies the drought/flood situation using station data, and then determines these classifications over an entire region by weighted averages, obtaining a regional drought/flood index. The other approach deduces a regional drought/flood index by weighting precipitation amounts, areas of positive/negative anomalies, and intensities at every station within the region. Some studies have directly used time series of EOF or rotated empirical orthogonal function (REOF) methods to determine the regional precipitation index. These studies have shown that the Z index can eliminate the discrepancy of different regional precipitation means, and that the Z series can meet the standard normal distribution and indicate drought and flood status to a certain extent. Therefore, the Z index is a better way to classify a single station's drought or flood situation. However, no consensus has been reached with respect to the regional scale.

Using data from 160 surface observation stations of the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA), Zhang and Wu (2001) studied the relationships between widespread Yangtze River valley drought/flood disasters and South Asian high pressure, establishing standardized yearly summer precipitation index sequences for 1958–99. Their results suggested that indices of annual summer precipitation in the 1970s were mainly negative, indicating a developing trend toward drought or less rain. However, there was a prominent interannual jump in 1979 from drought to flood. After the 1980s, rainfall over the Yangtze River valley generally increased. In the 1990s in particular, there were six years with more rainfall events than flood events, and four years were recorded as flooding years. Zhang and Wu (2001) divided typical drought and flooding years according to absolute values of the precipitation index. They found that six of 42 years (1958–99) could be defined as typical flooding years (namely, 1969, 1980, 1991, 1996, 1998 and 1999), with five of these years being after the aforementioned interannual jump. By comparison, another five years were typical drought years (1959, 1961, 1966, 1978 and 1985), and four of these preceded the interannual jump. Continued drought disasters in the 1960s and flooding and waterlogging events in the 1990s reveal a distinct difference.

Nevertheless, to objectively analyze drought/flood features in the Yangtze River valley, further studies must be carried out on many complex elements in the area, such as the geological terrain, its lakes, and others (Huang et al., 2008). Through analysis of annual hydrological data, drought/flood features in the valley can be described. These include soil moisture of the surrounding area, runoff, river conditions, and other hydrologic elements during the early stages of drought and flood events. Only by combining meteorological and hydrological information can such recognition be improved for interannual regularity of flooding and drought in the valley.

2. Data

To investigate the features of annual drought and flooding in the Yangtze River valley, we selected daily observation data of precipitation within the region covering the period 1960–2009, which were collected by the NMIC/CMA. Considering the quality and comparability of the various decadal data, we used reorganized data from 180 national-level observation stations covering the aforementioned period. The distribution of these stations is shown in Fig. 1.

To analyze comprehensively the influences of drought and flood features in the valley, which are reflected in annual hydrologic data of this area, we selected two representative hydrologic observation stations: Hukou Station (29.4°N, 116.1°E) at Poyang Lake, and Datong Station (30.7°N, 117.6°E) in the lower reaches of the valley. To perform a relative analysis, we used 1960–2009 runoff data from Hukou and Datong to represent the runoff amount in the middle reaches and entire valley, respectively. The analysis results, which integrated hydrologic and meteorological observation data, were able to provide base references for investigating drought and flood characteristics in the valley.

3. Summer drought/flood response to atmospheric and hydrological conditions

Our analysis of serious flood records from the last half-century suggested that, although disasters in the valley are generally caused by atmospheric circulations, the spatial and temporal variation of the geographic environment and hydrological geology means that the probability of different river branches being affected by flooding at the same time is low. However, since the Yangtze River valley is a large-scale water system, the hydrology of its various sections, from the upper to lower reaches, is closely related to the general situation of the entire valley. Usually, devastating floods affecting the valley are closely linked to the superposition of precipitation and hydrologic flood fronts. Different parts of the valley suffer droughts or floods nearly every year, with different causes. However, once a positive correlation occurs during the same period and at the same rate, the flood situation in different parts of the valley will soon become serious over the entire valley. Several recorded severe floods have occurred at a time when the entire river valley experienced heavy precipitation, and the middle and lower reaches were impacted by the superposition of flood fronts. For example, Datong Station recorded significant effects of devastating floods along the valley in 1954, 1998 and 1999 (http://www.cjh.com.cn/gis). In 1998, the valley experienced a long period of rainfall events when the mei-yu monsoon began. Soil moisture in areas hit by torrential rain approached saturation, and water levels of rivers and lakes remained very high. Consequently, large amounts of rainwater from subsequent severe rainstorms could only run into rivers, causing them and lakes to flood (Tao et al., 1998). Therefore, to improve understanding of interannual drought and flood conditions throughout the valley, a synthetic analysis of hydrologic data and rainfall should be carried out.

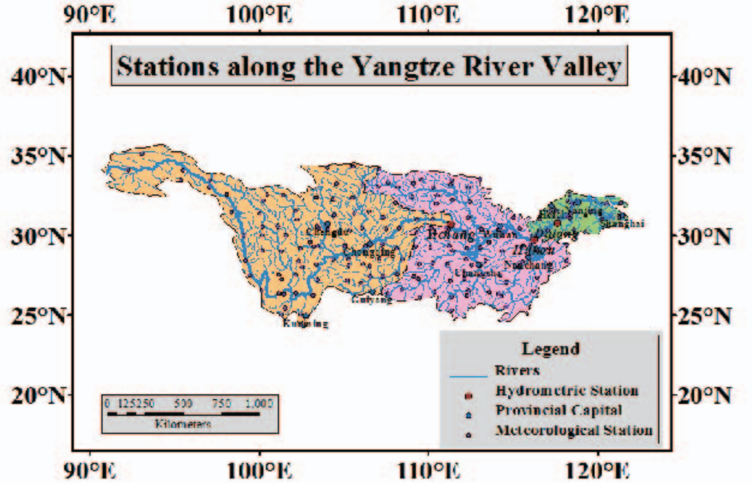

Fig. 1. Distribution of national-level meteorological observation stations within the Yangtze River valley. The yellow, pink and green areas are the upper, middle and lower reaches of the river, respectively.

3.1 *Runoff and summer rainfall in the middle reaches*

Hukou Station is situated at a key location in the middle reaches of the Yangtze River, with correlation analysis showing that water levels there are positively correlated with summer rainfall. Figure 2 displays the positive correlation between runoff from Poyang Lake at Hukou Station and total precipitation amounts from July to August in the middle reaches of the river during the period 1960–2009. Therefore, Hukou Station is an important indicator of critical water situations in the middle reaches of the river. In flooding years, the water level at Hukou depends on the rainfall over the main tributary, the Ganjiang River and sub-branches. This level also reflects composite atmospheric and hydrologic water conditions in the middle valley during periods of severe flooding, because of the positive adjustment of Poyang Lake and backflow effects of the flooding along the main river. Our study therefore suggests that hydrologic information from Dongting and Taihu lakes is consistent with the analysis of the relationship between this information and associated precipitation. This means that a positive adjustment of the lakes' sluice capacity during flooding and backflow effects of flooding on the main river are reflected in the hydrologic records, indicating an integrated atmosphere/land-surface determination of the water situation in the lower reaches of the river.

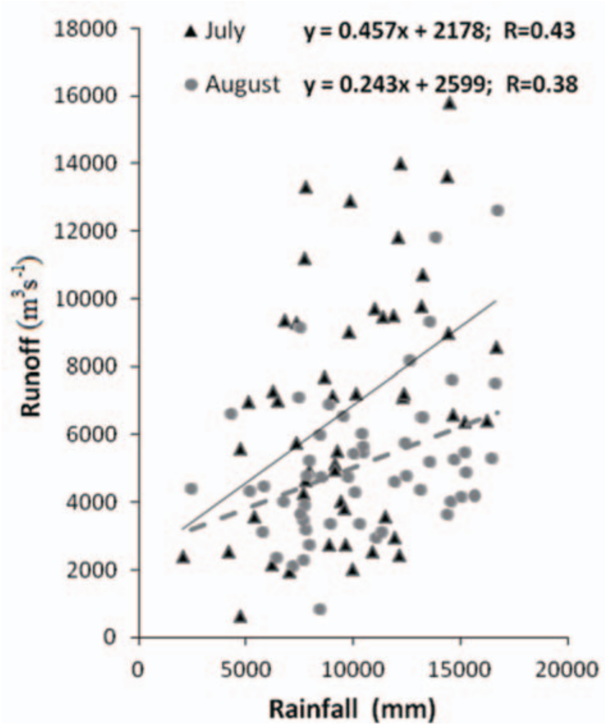

Fig. 2. Correlation between runoff from Poyang Lake at Hukou station and rainfall amount (July–August) in the middle reaches of the Yangtze River during 1960–2009.

3.2 *Summer rainfall and runoff in the lower reaches*

Based on the descriptions above, it is known that the annual summer drought/flood situation of the Yangtze River is closely related to the precipitation over the valley. This precipitation will eventually be expressed by variations of water volume in the Yangtze River and its subordinate rivers, which extend thousands of kilometers. This is because drought/flood trends tend to be influenced by interactions of environmental elements, including hydrologic features, the soil conditions of surrounding areas (dry or moist in early stages) and topographic features (energy efficiency of soil and water conservation), as well as complex, nonlinear interactions of other features of atmospheric circulation. If I represents the influence efficiency of precipitation in annual flood or drought in the valley, it may be expressed as

$$I = f(R, w, S, C, \ldots) , \quad (1)$$

where R, w, S, C, and $\ldots$ refer respectively to the rainfall amount in the valley, the water level or maximum runoff at key stations, valley soil features, atmospheric circulation features, and others (Fig. 3). Therefore, the summer drought/flood trend can be described by the distribution of index I.

As mentioned above, runoff preserves efficiency features, which are presented when precipitation causes flood. To simplify and concentrate the representativeness of various factors, we establish and discuss the relationship between meteorological and hydrological data of summer droughts and floods in the valley by considering runoff at key sites along the lower reaches of the river and rainfall amounts in the valley.

As a national-level hydrological observation station situated in the lower reaches of the river, Datong Station produces hydrologic data with very strong representativeness. Runoff data from this site were used to represent total runoff from the Yangtze River basin outlet. Using 1960–2009 runoff data and summer precipitation amounts over the entire valley, the level of correlation was determined (Fig. 4). As shown, precipitation is significantly correlated with runoff at Datong, with linear correlation coefficients of 0.56 for June, 0.53 for July and 0.51 for August, all at the 0.001 significance level. In general, runoff could be very different for the same rainfall amount. For example, when the precipitation amount is 30 000 mm, runoff could range between 45 000 and 73 000 $m^3 s^{-1}$, meaning neither can act as a proxy for the other. Therefore, a comprehensive index analysis is necessary.

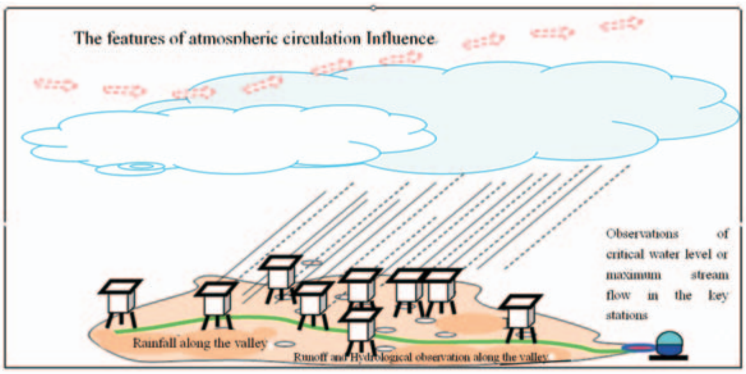

Fig. 3. Diagram of the composite response of the valley water situation (drought/flood) to precipitation in the valley, soil conditions in surrounding areas, topographic features and related atmospheric circulation features.

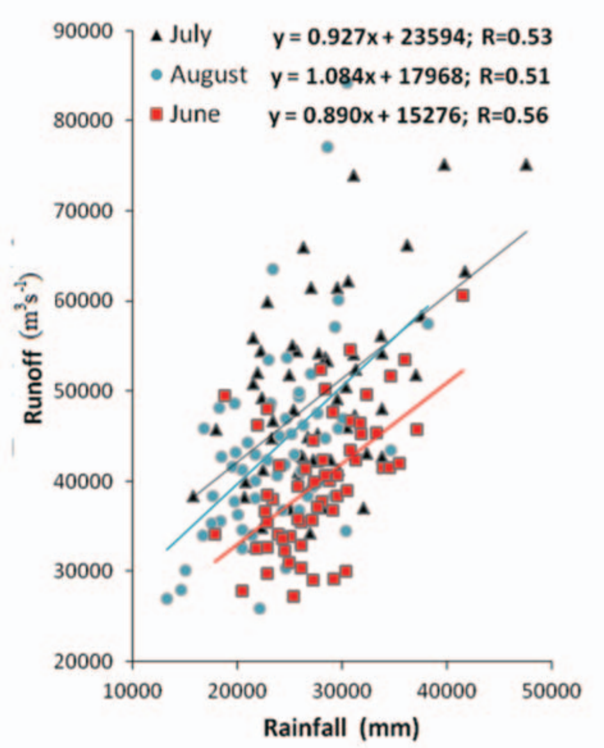

Fig. 4. Correlations between summer precipitation in the Yangtze River valley and runoff at Datong station during 1960–2009.

4. Meteorological and hydrological coupling index of summer droughts and floods

Annual flooding and drought in the Yangtze River valley result from the interaction of many factors. Rainfall over this region does not flow into the river directly, since the soil always absorbs a certain amount. In assessing the drought/flood situation, we must further investigate the effect of hydrologic conditions along the river (including runoff areas) for the conversion of precipitation into runoff (drought/flood) in the valley. Rainwater flows into different portions of the Yangtze after first soaking into the soil and the superposition of its extensive branch valleys. Therefore, records of runoff or water level can indicate the effect of precipitation responsible for the drought/flood situation. It is necessary to integrate meteorological and hydrological information to determine the drought/flood situation in the valley, by establishing a reasonable MHCI that reflects the objective reality of the annual drought/flood effect.

4.1 *Precipitation and hydrological indices*

Here, we provide an index to express interdecadal flooding and drought, which usually appear with alternating and volatile characteristics accompanying secular variation of the climate background. In studies of long-term weather or climate (e.g., flood and drought characteristics), the Z index is generally applied (Tan et al., 2002; Wei, 2004, 2007). This index is also used in mei-yu intensity change research (Zhou et al., 2010). Gao et al. (2006) formulated an e-exponent function to study flood and drought characteristics using long-term data. For describing the evolution of flooding and drought, it is important and common to adopt an e-exponent function. The e-exponent function enables a long time series to approximate a normal distribution, meaning we can use the new series to classify flood/drought according to its statistical characteristics (this will be done in future work).

Using a long time series standardized model of observation data (Zhang and Wu, 2001), we calculated annual summer standardized precipitation series (σ_γ) for the period 1960–2009, and runoff hydrological series (σ_w) over the same period, in the same way. For convenience of expression and calculation, we use σ to express σ_γ and σ_w, and define β as

$$\begin{cases} \beta_r = \begin{cases} \sigma_\gamma & \sigma > -1 \\ \dfrac{1}{C\sigma_\gamma} & \sigma < -1 \end{cases} \\ \beta_w = \begin{cases} \sigma_w & \sigma > -1 \\ \dfrac{1}{C\sigma_w} & \sigma < -1 \end{cases} \end{cases} \tag{2}$$

where σ_γ and σ_w are standardized precipitation and runoff amounts, respectively. If $\sigma<0$ in Eq. (2), the reciprocal term is taken to adapt to the real situation, and to avoid instability of the e-exponent function.

Now, c is a constant between 1 and 2 (1.2 here), and β_γ and β_w represent the index characteristics of the standardized precipitation and runoff amounts, respectively. Using the meteorological and hydrological indices σ_r and σ_w, we have

$$I(\sigma_\gamma) = \beta_\gamma \exp(-\sigma_\gamma) + |\beta_\gamma| \,, \tag{3}$$

$$I(\sigma_w) = \beta_w \exp(-\sigma_w) + |\beta_w| \,, \tag{4}$$

where β_r and β_w vary with interannual discrepancies of precipitation amount and runoff in the valley, as well as regional differences, and may be obtained by calculating σ_r and σ_w according to historical data, respectively. With Eqs. (4) and (5), based on annual total precipitation amount in the valley and annual total runoff at Datong Station during 1960–2009, we determine the precipitation index $I(\sigma_r)$ and hydrological index $I(\sigma_w)$ of the valley drought and flood situation. Figure 5 displays sequences of $I(\sigma_r)$ and $I(\sigma_w)$ during 1960–2009 at Datong Station, and the distributions show that:

(1) During that period, for most years, $I(\sigma_r)$ and $I(\sigma_w)$ have remarkably synchronous features, i.e., if $I(\sigma_r)$ is positive, $I(\sigma_w)$ is also positive, and vice versa. Therefore, we define years with such positive or negative phases of atmospheric and hydrological indices as typical flooding and dry years, respectively.

(2) For years in which both $I(\sigma_r)$ and $I(\sigma_w)$ are positive (1962, 1973, 1980, 1982, 1983, 1991, 1993, 1995, 1996, 1998, 1999 and 2002), years are defined based on the indices being $\geqslant 1$. Of those years, only 1973 and 2002 have a single index $\geqslant 1$, but its value is $\gg 1$. For years in which both $I(\sigma_r)$ and $I(\sigma_w)$ are negative, years with indices $\leqslant -1$ are defined as typical severe drought years. These include 1963, 1972, 1978 and 1988, among which 1978 has a single index of $\leqslant -1$, but its value is $\ll 1$.

(3) In many years, $I(\sigma_r)$ and $I(\sigma_w)$ have out-of-phase features. These years include 1964, 1965, 1967, 1968, 1969, 1974, 1975, 1979, 1986, 1987, 1992 and 2008. This indicates that descriptions of the two main indicators of annual drought/flood have a complex combination. To improve the descriptive ability of the index, further analysis is necessary on the composite effect of the two indices when out-of-phase.

(4) In out-of-phase years (1979 and 1986), the common feature is $I(\sigma_w) \leqslant -1$, and the hydrologic drought signal is stronger than the atmospheric flooding signal. It can be seen in Fig. 5 that during the period with out-of-phase information on a stronger hydrologic drought signal (including 1979), there are about 10 years with less precipitation. If that signal is stronger than the atmospheric flooding signal, drought or less rain is the major developing trend. The 1986 out-of-phase hydrologic drought signal ends. An out-of-phase character continues in 1987, but the signal is weaker than the atmospheric flooding signal. After that, the period with more rainfall enters a stable state, leading to a continuous flooding trend in the years 1991, 1993, 1995, 1996, 1998 and 1999. This phenomenon suggests that studying various features and the significance of atmospheric and hydrological indices is very important for analyzing the unsustainable characteris-

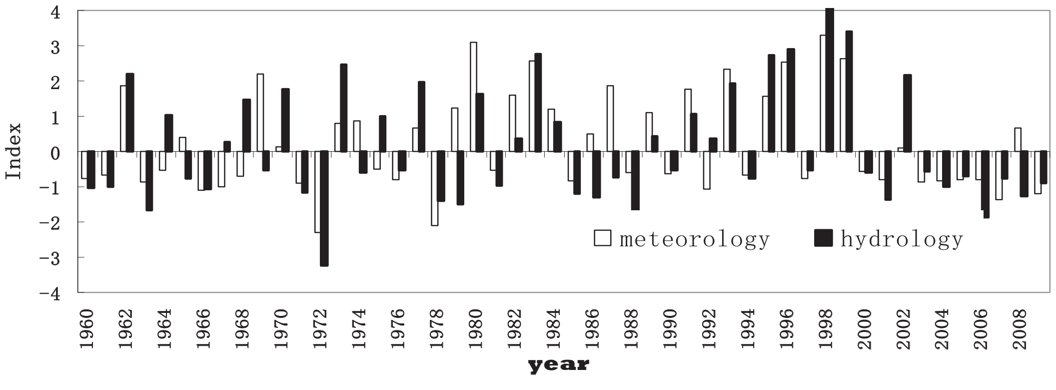

Fig. 5. Drought/flood indices for the Yangtze River valley [precipitation index $I(\sigma_r)$ for the entire valley and hydrological runoff index $I(\sigma_w)$ at Datong Station] during 1960–2009.

tics of conversion between drought and flooding. Such studies could provide reference for research on unsustainable changes of the monsoon climate (Zhang et al., 2008). Therefore, focusing on the superposition of inphase or out-of-phase meteorological and hydrological index signals and composite contributions can provide guidance and references in the annual and interannual assessment of drought and flooding, as well as diagnosis and prediction of the drought/flood situation in the Yangtze River valley. To reasonably syncretize the features and significance of hydrological and meteorological indices, we formulated one composite index to improve diagnosis of the summer drought/flood situation in the valley.

4.2 *Summer drought/flood and the relationship with MHCI*

To obtain meteorological and hydrological coupling characteristics of the summer water situation (drought/flood) in the valley, Eqs. (3) and (4) above were combined to define the coupling index

$$I(\sigma_\gamma, \sigma_w) = \beta' \exp(-\sigma') + \alpha \,, \qquad (5)$$

in which $\alpha = \sqrt{\beta_\gamma^2 + \beta_w^2}$, $\sigma' = \frac{1}{2}(\sigma_r + \sigma_w)$, and $\beta' = \frac{1}{2}(\beta_\gamma + \beta_w)$. Equation (5) represents the coupling index of precipitation and hydrologic information of the valley during the period 1960–2009 (Fig. 6). This figure shows that:

(1) The distribution of annual MHCI $I(\sigma_r, \sigma_w)$ from 1960 to 2009 can strongly reflect the characteristics of the annual drought/flood situation, with positive values of $I(\sigma_r, \sigma_w)$ for an abundant-rain year and negative ones for a dry or low-rain year.

(2) In years with a positive annual coupling index $I(\sigma_r, \sigma_w)$ from 1960 to 2009, typical flooding years with an index of $\geqslant$1 are 1962, 1970, 1973, 1977, 1980, 1982, 1983, 1984, 1991, 1993, 1995, 1996, 1998, 1999 and 2002. This result is consistent with research using hydrologic records from the two large lakes, Dongting and Poyang. For example, 1973 and 1995 are not listed as flooding years if only the rainfall amount is considered, but there was significant flooding. This is consistent with the findings of Li et al. (2004) and Min (2000), and of Zhou and Yue (2004), who found more floods and devastating hydrometeorological disasters in the Yangtze River valley during the 1990s. Comparing Figs. 6 and 5, we see that the distribution of typical flooding years is similar to previous studies and routine analyses, but with the addition of 1970, 1977, 1982 and 1984.

(3) By comparing Fig. 5 and earlier findings (Zhang and Wu, 2001), we see that extra flooding years determined by the coupling index value of $I(\sigma_r, \sigma_w) \geqslant 1$ (1970, 1977, 1982 and 1984) are those with the same phase of positive atmospheric and hydrological indices. This mainly refers to years with a positive and larger hydrological index, but smaller precipitation index (excluding 1982). This suggests that with a small precipitation amount across the entire valley, but a large hydrological index, high water levels can still occur, because flooding and waterlogging of tributaries and river valleys can increase the proportion of flood years.

(4) Typical drought years with negative $I(\sigma_r, \sigma_w)$ and $\leqslant -1$ include 1963, 1966, 1972, 1978, 1985, 1988, 2001, 2006, 2007 and 2009.

4.3 *The "new" cases identified by the MHCI*

4.3.1 *Drought years*

To enable us to analyze and distinguish from previous results, we carried out drought/flood assessment in the conventional way with a single piece of meteorological or hydrological information (see Fig. 5). Those

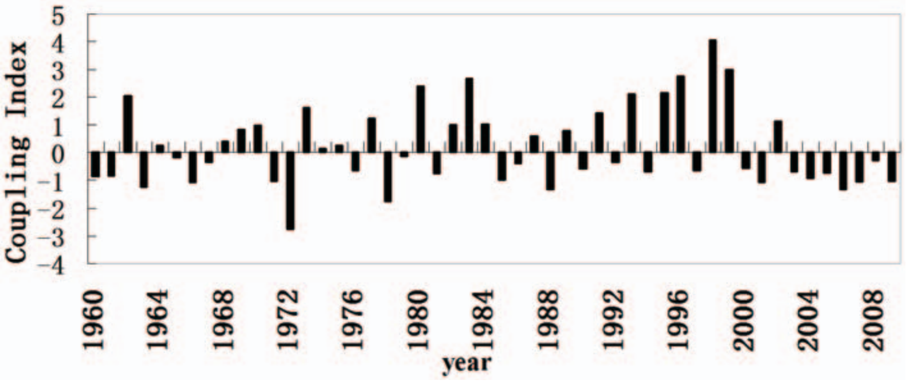

Fig. 6. Drought/flood coupling index in the Yangtze River valley, indicated by rainfall in the river valley and runoff at Datong station during 1960–2009.

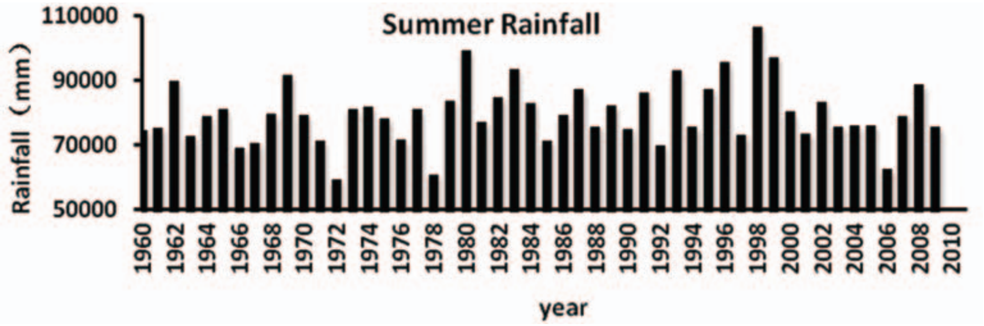

Fig. 7. Total summer precipitation over the entire Yangtze River valley during 1960–2009.

flood/drought years added via diagnosis of the coupling index could then be identified and are referred to here as "new" cases. Comparing Figs. 6 and 5, 1988 can be seen as one such newly-added drought year. Statistical analysis reveals that, in this year, the middle and lower reaches of the Yangtze River were affected by a severe drought disaster, unprecedented in the past 100 years. Beginning in early- to mid-June, scorching temperatures dominated large areas from the Huanghuai region to those reaches of the river, as well as the North China Plain and South China. High temperatures were 35°C–39°C, reaching 41°C in some areas. Geyang County in Jiangxi Province reported a maximum temperature of 41.4°C on 18 July. The total drought-affected area in the country was about 20.6667 million ha. Hunan Province is located in the main portion of the Yangtze River, yet rivers and lakes there at that time were almost dry. By the end of July 1988, 1.7 million people in the province were suffering from a lack of drinking water, and water storage in Dongting Reservoir in the Yangtze valley was 3.07 billion m^3 less than in the corresponding period of the previous year (Zhang et al., 2007).

4.3.2 *Flood years*

Using the coupling index $I(\sigma_r,\sigma_w)\geqslant 1$, 1970, 1973, 1977 and 2002 were added to the group of waterlogged years, all of which show the same phase of positive atmospheric and hydrological indices superimposed. The hydrological index is high and positive. Owing to the limitation of single atmospheric or hydrological data, these flooding years were likely overlooked within some conventional drought/flood analyses. For 1983 in particular, with its coupling index $I(\sigma_r,\sigma_w)\geqslant 2$, atmospheric index $I(\sigma_r)\geqslant 2.5$, and hydrological index $I(\sigma_w)\geqslant 2.5$, the coupling index is similar to cases of catastrophic floods in 1998 and 1999. Figure 7 shows the distribution of annual precipitation amount in the Yangtze River valley during 1960–2009. Analyzing the last 50 years' precipitation records in the valley (Fig. 7), we find that although 1983 is noted as a heavier rain year, it was likely removed from the series of flooding years in the valley (Zhang and Wu, 2001). In fact, 1983 has characteristics similar to the rainfall distributions of 1991 and 1998, which means that catastrophic floods mainly occurred around Taihu Lake and its upper reaches. In the period May–July 1983, Taihu Lake discharged about 2.92 billion m^{3}of floodwater into the Yangtze River from 13 sluices, of which 68 million m^3 flowed into Hangzhou Gulf, constituting 36.4% of the discharge capacity of Huangpu River (part of the Yangtze River). The flood evolution was such that large amounts of floodwater from the upper reaches flowed into Taihu Lake, and then the water rushed into tributaries and the Huangpu River, finally emptying into the Yangtze River. This resulted in abnormal water levels in its upper and lower reaches, and difficulties in releasing floodwater. In general, such evolution resembles that in 1954, 1991 and 1998, and has the basic characteristics of flood events in the Yangtze River valley (Wu, 2000). For this type of serious flooding, a study on only the distribution of rainfall amount during a given period cannot portray the complete flood situation. Sometimes, precipitation in the early stages of the major flood season (e.g., rainwater stored in large lakes or in reservoirs) may affect the water situation of the lower river during later stages, which depends on interactions reflected by the hydrologic records in the valley. Therefore, we conclude that the coupling index can successfully diagnose effects in extremely serious flood years via positive superposition of the two indices.

4.4 *Validation of the MHCI*

To test the reliability of the MHCI in terms of the summer drought/flood situation in the Yangtze River valley, we examined summer standardized precipitation sequences for the valley and conducted related analyses on the MHCI, using data from 1960–2009. Figure 8 shows the results of the analysis, indicating that the standardized annual distribution of precipitation has remarkable correlation with the coupling index of summer drought/flood. The correlation coefficient reaches 0.8217, greater than the 0.001 signif-

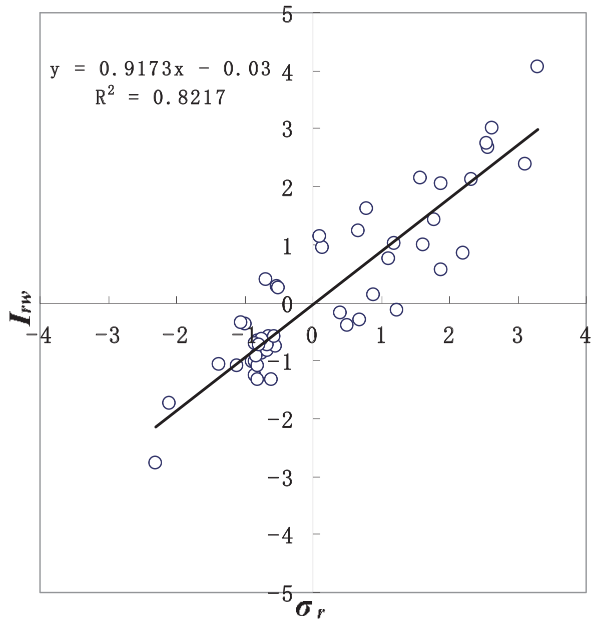

Fig. 8. Correlation of summer standardized rainfall amount in the Yangtze River valley and MHCI during 1960–2009.

icance level. This suggests the coupling index can indicate precipitation features very well.

Although the MHCI has a very significant correlation with summer atmospheric standardized rainfall amount, there are differences. For example, when the standardized precipitation amount is 1, the MHCI is 0.1–1.6, which represents different flood classes. In this case, a comprehensive index analysis is necessary.

5. Conclusions

(1) We analyzed hydrologic information from the representative Hukou and Datong Stations, the degree of correlation with Yangtze River valley precipitation, annual total precipitation in the valley, and annual total runoff at Datong Station during the period 1960–2009. From these analyses, we calculated the summer precipitation index $I(\sigma_r)$ and hydrological index $I(\sigma_w)$.

(2) We explored the features of $I(\sigma_r)$ and $I(\sigma_w)$ and their contributions to the drought/flood situation in the valley, revealing that the hydrologic information can depict nonlinear and continuity features of long-lasting drought conversion to flooding events. Comprehensive analysis of the annual phase difference between the atmospheric and hydrological indices, and their characteristics, is very useful for recognizing and predicting the annual drought/flood status.

(3) We demonstrated that solely using precipitation or hydrologic data to study and assess drought/flood events is likely to mean some critical events are missed. However, the 1960–2009 annual MHCI $I(\sigma_r,\sigma_w)$ is very effective and sensitive in reflecting annual drought/flood distribution characteristics. A positive MHCI $I(\sigma_r,\sigma_w)$ usually indicates a rainier or typical flood year, and a negative MHCI $I(\sigma_r,\sigma_w)$ a drought or low-rain year.

(4) Verification of the MHCI $I(\sigma_r,\sigma_w)$ based on 1960–2009 data suggests the summer MHCI is positively correlated with the annual distribution of precipitation. The correlation coefficient is as high as 0.82, exceeding the 0.001 significance level. This indicates that the MHCI for the Yangtze River valley developed herein can represent precipitation features very well.

Acknowledgements. This paper was supported by project GYHY201106050, the National "973" Program of China under Grant No. 2011CB403404, and Project No. 2009Y002.

REFERENCES

Chang, C. P., and T. C. Chen, 1995: Tropical circulations associated with southwest monsoon onset and westerly surges over the South China Sea. *Mon. Wea. Rev.*, **123**, 3254–3267.

Gao, B., Q. J. Chen, and D. D. Ren, 1998: Diagnosis and analysis on the serious drought/flood in the early stage of flooding season across the region of southern Jiangnan and northern Huanan. *J. Appl. Meteor. Sci.*, **10**(2), 219–226.

Gao, J. Y., Z. W. Deng, and X. L. Zou, 2006: Spatial/temporal features of drought/flood in Fujian for the past 4 decades. *Journal of Tropical Meteorology*, **22**(5), 491–497

Huang, Z. H., B. Xue, S. C. Yao, and Y. Pang, 2008: Lake evolution and its implication for environmental changes in China during 1950–2000. *Journal of Geographical Sciences*, **18**, 131–141, doi: 10.1007/s11442-008-0131-4.

Li, C. Y., and X. Qu, 2000: Evolution of large-scale atmospheric circulations accompanying the appearance of summer monsoon in South China Sea. *J. Atmos. Sci.*, **24**(1), 1–14.

Li, J. B., J. C. Qin, K. L. Wang, C. J. Liang, and H. Yuan, 2004: Response of Dongting Lake environmental system variation to hydrological situation. *Acta Geographica Sinica*, **59**(2), 239–248.

Lin, H., and B. Wang, 2002: The time-space structure of the Asian-Pacific summer monsoon: A fast annual cycle view. *J. Climate*, **15**(15), 2001–2019.

Lü, J. M., Q. Y. Zhang, S. Y. Tao, and J. H. Ju, 2006: The onset and advancing characteristics of summer monsoon in Asia. *Chinese Science Bulletin*, **51**(3), 332–338.

Ma, Y. F., 2003: Variations of the annual precipitation amount of the representative stations in Jiangsu province and the analysis on the series representativeness. *Journal of China Hydrology*, **23**(3), 45–51. (in Chinese)

Matsumoto, J., 1997: Seasonal transition of summer rainy season over Indochina and adjacent monsoon region. *Adv. Atmos. Sci.*, **14**(2), 231–245.

Min, Q., 2000: Variation of the shape and water conditions of Poyang Lake in the late 50 years and their relationship with reclamation. *Advances in Water Resources*, **11**(1), 76–81.

Ping, F., and Z. X. Luo, 2006: Differences existing in the impact factors of inter-annual variation and inter-annual scale variation during the flood season in Yangtze River valley. *Chinese Science Bulletin*, **51**(1), 104–109.

Tan, G. R., Z. B. Sun, and H. S. Chen, 2002: Study on drought and flood index. *Journal of Nanjing Meteorology College,* **25**(2), 153–158. (in Chinese)

Tao, S. Y., Q. Y. Zhang, and S. L. Zhang, 1998: Climatic background and large-scale circulation conditions for flood disasters in Yangtze River valley in 1998. *Climatic and Environmental Research*, **13**(4), 290–299.

Wang, J. Z., and M. C. Li, 1982: Cross-equator flow from Australian and the monsoon over China. *J. Atmos. Sci.*, **6**(1), 1–9.

Wang, J. Z., and P. W. Leftwich, 1984: A major low-level cross-equatorial current at 110°E during the summer and its relation to typhoon activities. *J. Atmos. Sci.*, **8**(4), 443–449.

Wang, Q. Y., 2004: Analysis on precipitation features and changing trend of the source area of Yangtze River. *Journal of China Hydrology*, **24**(1), 54–60. (in Chinese)

Wang, S., J. Lu, B. W. Wu, and Z. H. Chen, 2008: Research on the summer precipitation variation in Anhui Province and the influence on drought-flood. *Anhui Agriculture Science*，**36**(7), 2870–2873. (in Chinese)

Wei, F. Y., 2004, Characterization of drought strength in North China and its climatic variation. *Journal of Natural Disasters,* **13**(2), 32–38. (in Chinese)

Wei, F. Y. 2007: Modern diagnostic techniques for climatologically statistics. *China Meteorology Press*, 267–281. (in Chinese)

Wu, H. Y., 2000: Comparison and analysis of typical meiyu flood disasters in Taihu basin. *Journal of China Hydrology*, **20**(4), 54–58. (in Chinese)

Xu, X. D., Q. J. Miao, S. J. Zhang, and D. B. Tan, 2004: Hydro-meteorological model for the strong signal sensitive areas in the flooding process over Yangtze River valley. *Journal of Yangtze River Science Research Institute*, **21**(3), 17–20.

Zhang, J. M., Z. X. Li, and X. P. Zhang, 2007: Analysis on multi-time scales of the precipitation in the past 50 years in Changsha region. *Journal of China Hydrology*, **27**(6), 78–81.

Zhang, Q., and G. X. Wu, 2001: Relations between large-range drought/flood across Yangtze River valley and high pressure in southern Asia. *Acta Meteorological Sinica*, **59**(5), 569–577.

Zhang, R. H., 2006: Climate observing system and its related key issues. *Journal of Applied Meteorological Science*, **10**(6), 705–710. (in Chinese)

Zhang, R. H., B. Y. Wu, P. Zhao, and J. P. Han, 2008: The decadal shift of the summer climate in the late 1980s over eastern China and its possible causes. *Acta Meteorologica. Sinica*, **22**(4), 436–445.

Zhou, G. L., and Z. H. Yue, 2004: Summary of the serious hydro-meteorological events in China since 1990. *Journal of China Hydrology*, **24**(1), 28–31. (in Chinese)

Zhou, H. F., R. Fang, and J. J. Zhang, 2010: Prediction for drought/flood during the flood season based on SVD method and modified Z-index and its application. *Climatic and Environmental Research*, **15**(1), 64–72.