Spatiotemporal pattern variations of daily precipitation concentration and their relationship with possible causes in the Yangtze River Delta, China

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ABSTRACT
Understanding the spatiotemporal pattern of precipitation concentration is important in the water cycle under changing environments. In this study, the daily precipitation concentration index in the Yangtze River Delta in China is calculated based on the Lorenz curves obtained from the observed data of 36 meteorological stations from 1960 to 2017, and spatiotemporal pattern variations and their possible causes are investigated. The driving forces of elevation, SUNSPOT, El Niño-Antarctic Oscillation, Pacific Decade Oscillation, and Arctic Oscillation are detected with correlation and wavelet analysis. Results show that, the daily precipitation concentration index ranges from 0.55 to 0.62 during the study period, 22 of 36 stations (accounting for 61%) show increasing trends, while three stations increase significantly at the 95% significance level. Relationship analysis indicates that the daily precipitation concentration shows a slightly negative correlation with elevation, while the relationships with SUNSPOT, El Niño-Antarctic Oscillation, Pacific Decade Oscillation, and Arctic Oscillation are complicated and diverse, there are different correlations and significance levels in different years. Further analysis shows that SUNSPOT is significantly correlated with El Niño-Antarctic Oscillation, Pacific Decade Oscillation, and Arctic Oscillation, which suggests that SUNSPOT may be an important factor that drives the changes of the three large-scale atmosphere circulation factors and causes precipitation concentration changing indirectly. These results provide further understandings of precipitation variations, which are meaningful for regional flood risk management under climate change.

Key words: daily precipitation concentration, large-scale atmosphere circulation, Lorenz curve, spatiotemporal pattern, Yangtze River Delta

HIGHLIGHTS
• Spatiotemporal variations of daily precipitation concentration in the Yangtze River Delta are investigated.
• Daily precipitation concentration shows a strong spatial heterogeneity overall.
• Large-scale atmospheric circulation and SUNSPOTS are possible driving forces.

INTRODUCTION
Precipitation plays an important role in the water cycle and is one of the most important meteorological factors that are closely related to human beings (Guo et al. 2010; Zannoni et al. 2019; Yin et al. 2021). Precipitation is the major source of water resources for many areas, while heavy precipitation may also induce disasters, such as floods, urban inundation, dam breaks, and other hazards (Singh et al. 2011; Imam et al. 2018; Tabari 2020). It is because precipitation is the most changeable climatic variable in the whole water cycle, and understanding the spatiotemporal variations of precipitation is meaningful for water-related management under climate change (Kysely et al. 2012; Arab & Conoscenti 2017). In recent years, with the impacts of global climate change and rapid urbanization, precipitation characteristics of many regions are changing (Pumo et al. 2017), such as precipitation extremes, precipitation intensity, and precipitation concentration (Kaspersen & Halsnes 2017; Gao et al. 2018; Guo et al. 2018; Li et al. 2019; Chen et al. 2020). In particular, the frequencies of extreme precipitation in some areas have increased significantly and resulted in aggravation of flood disasters (Maggioni & Massari 2018; Hanbeen et al. 2020). Changes in precipitation characteristics pose challenges to water-related risk management strategies and are of great practical significance for social development (Arab & Mesgari 2019; Wang et al. 2019a, 2019b;
Breugem et al. 2020; Arab Amiri & Gocic 2021). Moreover, precipitation analysis also provides vital understandings for climate change, which has received wide attention (Rahman & Islam 2019; Guo et al. 2020; Yang et al. 2020a, 2020b).

The daily precipitation concentration index (CID) is an index in exploring the structural features for precipitation (Yin et al. 2021). CID defines the precipitation amount and its temporal distribution in a period and reflects the rainfall intensity (Rahman & Islam 2019). Since precipitation concentration index has been developed by Martin-Vide (2004), it has been widely used in the analysis of precipitation concentration and their spatiotemporal variations in many regions, such as Northeast China (Wang et al. 2019a, 2019b), Pearl River basin (Zheng et al. 2017), Central-Southern Chile (Sarricolea et al. 2019), the United States (Royé & Martin-Vide 2017), Europe (Vyshkvarkova et al. 2018), and even global scale (Monjo & Martin-Vide 2016). Studies have shown that precipitation concentrations are significantly changed in some areas; for example, Rahman & Islam (2019) reported that the precipitation day frequency indices have significantly increased in Bangladesh; Yang et al. (2020a, 2020b) found that there are decreasing trends of precipitation concentration and increasing trends of precipitation diversity in Central Asia over past decades; Yin et al. (2021) investigated the precipitation concentration and their relationship with the precipitation structure in the Huai River basin. Findings from the studies around the world remind people to pay more attention on precipitation concentration.

Spatiotemporal pattern variations of precipitation concentration and their driving forces are being strengthened recently (Zheng et al. 2017; Yang et al. 2020a, 2020b). Possible driving forces in changing of the precipitation concentration mainly include large-scale atmospheric circulation factors, SUNSPOTS, and topography (Zheng et al. 2017; Rahman & Islam 2019; Yang et al. 2020a, 2020b). Among them, mostly used large-scale atmospheric circulation factors include North Atlantic Oscillation (NAO), Atlantic Oscillation (AO), Pacific Decadal Oscillation (PDO), and El Niño Southern Oscillation (ENSO), different studies selected different indexes according to the study areas. For example, PDO, NAO, and East Asian summer monsoon index (EASMI) are selected in the study at Northeast China (Wang et al. 2019a, 2019b); Indian summer monsoon (ISM), Indian Ocean Dipole (IOD), ENSO, and NAO are selected for the study at the Beas River basin, India (Yin et al. 2016); El Niño Modoki Index (EMI), PDO, and NAO are selected for studies at Central Asia (Yang et al. 2020a, 2020b). In terms of methodology, the main spatiotemporal analysis methods used include Mann – Kendall (M – K) test, Sen’s method, Pettitt test, and spatial analysis (Shi et al. 2013; Arab et al. 2018; Wang et al. 2019a, 2019b; Gocic & Amiri 2021). For driving force analysis, mainly used statistics methods are correlation analysis, wavelet analysis, and random forest (Zheng et al. 2017; Rahman & Islam 2019).

The Yangtze River Delta is one of the most economically developed and densely populated areas in China (Ye et al. 2018), but faces severe flood disasters leading to large economic losses every year (Peng et al. 2020; Sun et al. 2020). As coastal areas, deltas are more sensitive to global climate change (Liang et al. 2011). Previous studies on precipitation variations of the Yangtze River Delta mainly focused on extreme precipitation changes (Pei et al. 2018), impacts of urbanization on precipitation (Lu et al. 2019), and dryness/wetness changes (Wang et al. 2016), which are the basis of explorations about spatiotemporal pattern variations of precipitation concentration.

This study focuses on spatiotemporal pattern variations of daily precipitation concentration and their relationship with possible causes. The objectives are to explore (a) temporal trends of daily precipitation concentration; (b) spatial pattern variations of daily precipitation concentration; and (c) relationship between daily precipitation concentration with possible causes, in the Yangtze River Delta, during 1960 and 2017. The main innovation of this study is applying the Lorenz curve method to analyze the precipitation concentration and then explore their driving forces in a climate-sensitive area. The results will help to improve the understanding of precipitation of variations and promote flood risk management in the study area.

STUDY AREA AND DATA

The Yangtze River Delta is located at the end of the Yangtze River basin and facing the Pacific, with a total area of 109,813 km², including parts of the three provinces of Jiangsu, Shanghai, and Zhejiang in China (Mei et al. 2021). The average annual rainfall of the Yangtze River Delta is about 1,050 mm, which is mainly concentrated in the flood season from May to October, and usually accounts for about 70%. Recently, studies reported that the rainfall characteristics in the Yangtze River Delta have to be changed; the variations include the total amount, intensity, and spatial distribution of precipitation (Zhou et al. 2016; Pei et al. 2018; Lu et al. 2019). Daily precipitation concentration is an important factor that characterizes the precipitation structure, which is closely related to flood disasters in the Yangtze River Delta (Zhou et al. 2016). Based on
the previous study (Mei et al. 2021), this study continues to analyze the changing rainfall regimes of the Yangtze River Delta and mainly focused on the daily precipitation concentration.

The daily precipitation data for the Yangtze River Delta and its surroundings are collected from the National Meteorological Information Center of China (Mei et al. 2021). Before further study, recorded data are discarded when the data observation starting and ending time are inconsistent, and stations that miss data for >1 year are also eliminated. Therefore, daily precipitation data of 36 stations in 58 years from 1960 to 2017 are collected for this study, and the detailed information of the selected stations are listed in Table 1.

To explore the possible causes of the daily precipitation concentration changes, elevation, and SUNSPOTS, three large-scale atmospheric circulation factors are selected as potential driving force factors to be analyzed according to the previous studies (Zheng et al. 2017; Rahman & Islam 2019; Yang et al. 2020a, 2020b). Data sources of elevation, SUNSPOTS, ENSO, PDO, and AO are listed in Table 2 (Huang et al. 2019).

**METHODOLOGY**

**Lorenz curve**

The CID is an important indicator that is widely used in the analysis of the precipitation structure and was proposed by Martin-Vide (2004). According to the theory, calculation steps are as follows: first, daily precipitation values are classified with 1-mm precipitation amount as class interval in an ascending order. Second, based on the classified daily precipitation data, the number of rainy days (Ni) and the corresponding precipitation amount (Pi) are used to calculate the percentage of accumulated rainy days and the corresponding accumulated precipitation. Finally, the cumulative frequency of rainy days (X or Sum (Pi)) is plotted against the precipitation amount (Y or Sum (Ni)), their relationship is an exponential curve, and

| Station name | Station number | Longitude (E) | Latitude (N) | Elevation | Station name | Station number | Longitude (E) | Latitude (N) | Elevation |
|--------------|----------------|---------------|--------------|-----------|--------------|----------------|---------------|--------------|-----------|
| Xuyi (XuY)   | 58138          | 118.52        | 32.98        | 40.8      | Huzhou (HuZ) | 58450          | 120.05        | 30.87        | 7.4        |
| Funing (FuN) | 58143          | 119.85        | 33.80        | 4.8       | Hangzhou (HangZ) | 58457          | 120.17        | 30.23        | 41.7       |
| Dafeng (DaF) | 58158          | 120.45        | 33.17        | 3.1       | Pinghu (PingH) | 58464          | 121.12        | 30.65        | 4.0        |
| Chuzhou (ChuZ)| 58236         | 118.25        | 32.35        | 33.5      | Cixi (CiX)   | 58467          | 121.27        | 30.20        | 4.5        |
| Nanjing (NanJ)| 58238         | 118.90        | 31.93        | 35.2      | Dinghai (DingH) | 58477          | 122.10        | 30.03        | 35.7       |
| Gaoyou (GuangZ)| 58241        | 119.45        | 32.80        | 5.4       | Tunxi (TunX) | 58531          | 118.28        | 29.72        | 142.7      |
| Dongtai (DongT)| 58251        | 120.28        | 32.85        | 3.3       | Chunan (ChunA) | 58543          | 119.02        | 29.62        | 171.4      |
| Rugao (RuG)  | 58255          | 120.57        | 32.37        | 6.4       | Jinhua (JinH) | 58549          | 119.65        | 29.12        | 62.6       |
| Nantong (NanT)| 58259         | 120.98        | 32.08        | 4.8       | Shenchangzhou (ShengZ) | 58556          | 120.82        | 29.60        | 104.3      |
| Lvi (LvS)    | 58265          | 121.60        | 32.07        | 3.6       | Yiwu (YiW)   | 58557          | 120.08        | 29.33        | 90.0       |
| Maanshan (MaAS)| 58336       | 118.57        | 31.70        | 80.0      | Qinzhou (QinZ) | 58562          | 121.55        | 29.78        | 5.0        |
| Changzhou (ChangZ)| 58343     | 119.98        | 31.87        | 4.4       | Shipu (ShiP) | 58569          | 121.95        | 29.20        | 128.4      |
| Suyang (SuY) | 58345          | 119.50        | 31.43        | 5.9       | Chushou (ChuZ) | 58633          | 118.90        | 29.00        | 82.4       |
| Wuxi (WuX)   | 58354          | 120.35        | 31.62        | 3.2       | Lishui (LiS) | 58646          | 119.93        | 28.47        | 59.7       |
| Kunshan (KunS)| 58356         | 121.00        | 31.40        | 3.2       | Xianju (XianJ) | 58652          | 120.72        | 28.87        | 83.0       |
| Wuxiandongshan (WuX)| 58358 | 120.43        | 31.07        | 16.7      | Honghung (HongJ) | 58665          | 121.42        | 28.62        | 4.6        |
| Baoshan (BaoS)| 58362         | 121.45        | 31.40        | 5.5       | Dachendao (DaC) | 58666          | 121.90        | 28.45        | 86.2       |
| Ningguo (NingG)| 58436         | 118.98        | 30.62        | 87.3      | Yuhuan (YuH) | 58667          | 121.27        | 28.08        | 95.9       |
the general formula can be described as the following (Shi et al. 2013; Huang et al. 2019):

\[ Y = aX \exp(bX) \]  

(1)

In Equation (1), \( a \) and \( b \) represent constants obtained by the least square method. The curve drawn by formula (1) is called the Lorenz curve (Shaw & Wheeler 1994), which was first used by economists (Lorenz 1905). The area enclosed by the Lorenz curve and the quadrant bisector is denoted as \( A \), the greater the value of \( A \), the greater the CID (Wang et al. 2019a, 2019b).

The area under the Lorenz curve could be calculated as follows (Wang et al. 2019a, 2019b):

\[ A = \frac{10,000}{2} \int_0^{100} aX\exp(bX)dX \]  

(2)

Then, CID can be calculated as follows:

\[ CID = \frac{2A}{10,000} \]  

(3)

**M – K test**

The M – K test is employed to detect the trends of CID in this study, which is a widely used trend test method proposed by Mann and Kendall (Mann 1945; Kendall 1975). More detailed procedures of the M – K method could be found in Zheng et al. (2017). For the M–K method, the positive value of \( Z \) represents an upward trend and the negative value represents a downward trend (Song et al. 2019). When \(|Z| > 1.64\), it means that the trend of the sequence has a significance level of 90%. When \(|Z| > 1.96\), it means that the trend of the sequence has a significance level of 95% (Zheng et al. 2017).

**Wavelet and correlation analysis**

Wavelet analysis is suitable for meteorological time series and has been widely used in many similar studies (Shi et al. 2013; Song et al. 2019). Investigations of the covariance of two series \( X \) and \( Y \) are defined as cross-wavelet analysis, which are proposed by Torrence & Compo (1998), the cross-wavelet spectrum of two time series \( X \) and \( Y \) with wavelet transforms \( W_X \) and \( W_Y \) as

\[ W_{XY}(s, t) = W_X(s, t)W_Y^*(s, t) \]  

(4)

where * represents complex conjugation, and the cross-wavelet power is defined as \(|W_{XY}(s, t)|\). The \( W_{XY} \) phase angle describes the phase relationship between \( X \) and \( Y \) in time – frequency space (Jevrejeva et al. 2003).

Furthermore, wavelet coherence represents the intensity of the covariance in time – frequency space and is defined as follows (Song et al. 2019):

\[ R^2(s, t) = \frac{|S(f^{-1}W_{XY}(s, t))|^2}{S(f^{-1}W_X(s, t)) \cdot S(f^{-1}W_Y(s, t))} \]  

(5)

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**Table 2 | Data sources of this study**

| Symbol | Contents | Data source |
|--------|----------|-------------|
| DEM    | Elevation | http://www.gscloud.cn/ |
| SUNSPOT| Sunspots  | http://sidc.oma.be/silso/dayssnplot |
| ENSO   | El Niño-Antarctic Oscillation | http://www.esrl.noaa.gov/psd/data/correlation/nina34.data |
| PDO    | Pacific Decade Oscillation | http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data |
| AO     | Arctic Oscillation | http://www.ncdc.noaa.gov/teleconnections/ao.php |
where $S$ stands for a smoothing operator in both time and scale. More detailed information about it can be referred in Torrence & Webster (1999), and the detailed implementation of the calculation could be found in Song et al. (2019).

**RESULTS AND DISCUSSIONS**

Validation of the Lorenz curve

According to the calculation results, the curves of the 36 rainfall stations are plotted as shown in Figure 1. Furthermore, Table 3 shows the CID values with coefficients $a$ and $b$ for the 36 stations. Figure 1 indicates that the cumulative percentage of precipitation in the 36 stations are well-matched, and all $R^2$ values shown in Table 3 are $>0.9$, which suggests that the curves are fitting well. The results mean that the Lorenz curve is suitable for the replication of the daily precipitation concentration behaviors in the Yangtze River Delta.

It can be seen from Table 1 that the values of CID range from 0.55 to 0.62, the highest value (0.62) of CID is observed at the Funing and Dafeng stations, whereas the lowest value (0.55) is identified at the Jinhua station. Moreover, the annual total precipitation ranges from 969.3 to 1,715.5 mm. For the study area, abundant precipitation with high daily precipitation concentration may lead to frequent flood in the Yangtze River Delta. Thus, more in-depth analysis of the precipitation variations is important for flood risk management under changing environments (Zheng et al. 2017; Wang et al. 2019a, 2019b).

Spatial distribution of average CID in decades

The CID values for 36 stations of the Yangtze River Delta from 1960 to 2017 are calculated. Figure 2 shows the spatial distributions of CID from 1960 to 2010 per decade, for all decades excluding 1970s. The distribution pattern of CID is also high in the north and part of southeast, while lower in the west, with strong spatial heterogeneity. For different provinces, CID in most areas of Jiangsu and the southern area of Zhejiang are higher, while the CID of Shanghai is always in the middle. In terms of time series, the CID is lowest in the 1970s, but in all the decades, the average CID is $>0.5$, and ranges from 0.5311 to 0.6475. In general, CID results in the Yangtze River Delta indicate that the daily precipitation of the study area is relatively concentrated in a year (Wang et al. 2016; Zhou et al. 2016).

Spatiotemporal characteristics of variation trends of CID

Based on the M–K method, the trends of annual total precipitation and CID of 36 rainfall stations from 1960 to 2017 are tested, and the results are shown in Figure 3. For annual total precipitation, 14 of the 36 rainfall stations exhibit significant increasing trends at 90% significance level; among them, 11 are above the 95% and five are above the 99% significance level.
In terms of spatial distribution, most of the sites where the annual total precipitation has significant increasing trends are located in the eastern coastal area of the study area. Different with annual total precipitation, although most of the stations (22 of 36) showed upward trends in the CID, there are three stations with significant trends, the remaining 14 stations show downward trends, and one of them decreased significantly at the 95% significance level.

For further elevation of CID in the Yangtze River Delta, four representative stations located in the northern, medium, and southern of the study area, Rugao, Ningguo, Tunxi and Hongjia, are selected for specific analysis. Figure 4 shows the Lorenz curves, Figure 6 shows the linear trends, and Figure 7 exhibits the M–K trend test results of the four representative stations.

| Station name   | Station number | ATP (mm) | CID | a   | b   | Z   | R²   |
|----------------|----------------|----------|-----|-----|-----|-----|------|
| Xuyi (XuY)     | 58138          | 1033.4   | 0.61| 0.034| 0.035| 0.389| 0.993|
| Funing (FuN)   | 58143          | 969.3    | 0.62| 0.031| 0.036| −1.368| 0.996|
| Dafeng (DaF)   | 58158          | 1083.8   | 0.62| 0.033| 0.036| 0.792| 0.998|
| Chuzhou (ChuZ)| 58236          | 1064.6   | 0.61| 0.036| 0.035| 0.852| 0.995|
| Nanjing (NanJ)| 58238          | 1085.9   | 0.60| 0.038| 0.034| 0.349| 0.998|
| Gaoyou (GuangZ)| 58241         | 1041.3   | 0.60| 0.037| 0.035| 0.845| 0.983|
| Dongtai (DongT)| 58251          | 1072.2   | 0.61| 0.034| 0.035| 0.698| 0.911|
| Rugao (RuG)    | 58255          | 1083.0   | 0.60| 0.033| 0.034| 0.201| 0.955|
| Nanjing (NanJ)| 58259          | 1105.1   | 0.59| 0.040| 0.034| 1.771| 0.983|
| Rugao (RuG)    | 58265          | 1079.6   | 0.60| 0.040| 0.034| 1.476| 0.910|
| Maanshan (MaAS)| 58336         | 1086.8   | 0.58| 0.047| 0.032| 1.798| 0.981|
| Changzhou (ChangZ)| 58343     | 1135.6   | 0.59| 0.042| 0.033| 1.020| 0.996|
| Suyang (SuY)   | 58345          | 1166.4   | 0.57| 0.051| 0.031| −0.080| 0.998|
| Wuxi (WuX)     | 58354          | 1121.9   | 0.58| 0.047| 0.031| 0.228| 0.991|
| Kunshan (KunS) | 58356          | 1111.9   | 0.58| 0.048| 0.031| 0.470| 0.977|
| Wuxian (WuX)   | 58358          | 1143.8   | 0.57| 0.052| 0.030| −1.476| 0.993|
| Baoshan (BaoS) | 58362          | 1128.9   | 0.58| 0.045| 0.032| −0.201| 0.992|
| Ningguo (NingG)| 58436          | 1444.7   | 0.56| 0.055| 0.029| −2.147| 0.992|
| Huzhou (HuZ)   | 58450          | 1286.7   | 0.56| 0.054| 0.030| −0.188| 0.983|
| Hangzhou (HangZ)| 58457        | 1418.9   | 0.55| 0.059| 0.029| −0.013| 0.999|
| Pinghu (PingH) | 58464          | 1232.8   | 0.58| 0.049| 0.031| 0.496| 0.976|
| Cixi (CiX)     | 58467          | 1332.0   | 0.57| 0.052| 0.030| 0.523| 0.997|
| Dinghai (DingH)| 58477          | 1386.4   | 0.58| 0.048| 0.032| 1.301| 0.996|
| Tunxi (TunX)   | 58531          | 1715.5   | 0.59| 0.040| 0.033| 3.595| 0.998|
| Chunan (ChunA) | 58543          | 1506.7   | 0.57| 0.050| 0.031| 0.590| 0.996|
| Jinhua (JinH)  | 58549          | 1446.0   | 0.55| 0.056| 0.029| 1.234| 0.998|
| Shengzhou (ShengZ)| 58556       | 1313.2   | 0.56| 0.056| 0.029| 1.328| 0.999|
| Yiwu (YiW)     | 58557          | 1373.7   | 0.56| 0.054| 0.029| 1.422| 0.999|
| Qinzhou (QinZ) | 58562          | 1439.4   | 0.57| 0.051| 0.030| −0.376| 0.993|
| Shipu (ShiP)   | 58569          | 1418.4   | 0.59| 0.043| 0.032| 1.207| 0.997|
| Chushou (ChuZ)| 58633          | 1678.8   | 0.57| 0.048| 0.031| −0.496| 0.997|
| Lishui (LiS)   | 58646          | 1411.0   | 0.56| 0.055| 0.029| −0.657| 0.992|
| Xianju (XianJ)| 58652          | 1444.1   | 0.58| 0.046| 0.031| −0.563| 0.985|
| Hongjia (HongJ)| 58665          | 1517.7   | 0.60| 0.037| 0.035| 0.040| 0.977|
| Dancheng (DaC)| 58666          | 1563.7   | 0.61| 0.036| 0.035| −0.510| 0.995|
| Yuhuan (YuH)   | 58667          | 1356.5   | 0.60| 0.037| 0.034| −0.765| 0.996|

In terms of spatial distribution, most of the sites where the annual total precipitation has significant increasing trends are located in the eastern coastal area of the study area. Different with annual total precipitation, although most of the stations (22 of 36) showed upward trends in the CID, there are three stations with significant trends, the remaining 14 stations show downward trends, and one of them decreased significantly at the 95% significance level.

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Figure 4 displays the calculated cumulative number of precipitation days versus the amount of accumulated precipitation for four representative stations. Highly fitted curves ($R^2 > 0.97$ for the four stations) indicate that the Lorenz curve can be used for testing the daily precipitation concentrations. The curves in Figure 5 also indicate that precipitation of the four stations has uneven temporal distributions, with the values of CID $>0.5$ due to notably high precipitation levels and a large proportion rainfall amount in the flood season.

Figure 5 shows the linear trends in CID values for the four representative stations from 1960 to 2017, the results show that CID values of the four representative sites have obvious inter-annual changes, and the change trends are not consistent. Among them, the CID values of Rugao and Ningguo show downward trends, while Tunxi and Hongji show upward trends. Furthermore, from the results of the 5-year moving average results, the CID values of the four stations show downward trends in the last 10 years.

The M–K test results of CID time series for the four representative stations are presented in Figure 6. The CID values of Rugao show downward trends in 1961–1980, 1983–1988, and 2001–2015, while the change is not significant. The CID values of the Ningguo station show downward trends in 1962–1983 and 1989–2017, among them, from 1971 to 1974 and 2015 to 2017, there is downward trend significant, and CID time series has a decreasing trend at 95% significance level during 1960–2017. The CID value of the Tunxi station showed an upward trend in 1977–2017, and there is an upward trend of the CID time series at the 99% significance level during the study period. At the same time, it can be seen from
the M–K inspection chart that there is abrupt changing point at 1987. The CID value of the Hongjia station is roughly divided into two stages: showing a downward trend from 1962 to 2006 and showing an upward trend from 2007 to 2017; overall, the CID time series of this station changed insignificantly.

Correlation between annual CID and elevation

Figure 7 presents the scatter plot of CID versus elevation per decade. It can be seen from Figure 7 that CID and elevation are negatively correlated in the Yangtze River Delta, indicating that the higher the altitude, the lower the CID. In 1960s, 1980s, and 2010s, the CID declined relatively quickly with elevation, while the CID of other decades slowly changed with elevation. The statistical results show that the highest absolute value of the first-term coefficients of the regression functions is 0.0002, and the $R^2$ ranges from 0.0064 to 0.215, revealing that the correlation between CID and elevation is not significant, and elevation is not a dominant factor that affects CID in the Yangtze River Delta (Zheng et al. 2017).

Relationship between CID and large-scale atmospheric circulation

To explore the possible driving forces of CID evolution, the relationships between CID and the possible causes are analyzed based on the cross-wavelet analysis. Figure 8 presents the cross-wavelet transform results of CID and AO, ENSO, PDO, and SUNSPOT time series. In the figures, red means strong correlation and blue means weak correlation. Thick black line is the boundary of the wavelet cone, which is the effective spectral value area, and thick black contour represents the 95% significance level. The arrow represents the phase difference, → indicates that the phases of the time series are the same and ← indicates that the phases of the time series are opposite (Song et al. 2019).

Relationship with AO

Figure 8(a) presents the wavelet coherence between regional average CID and AO. Figure 8(a) shows that CID and AO have a significant negative correlation during the period before 1970 (at the scale of 2–3 years) and 1975 (at the scale of 2–3 years), respectively. While in the period of 2009 (at the scale of 1–2 years), there is a significant negative correlation between CID
and AO. In most other years of 1960–2017, CID and AO have a positive correlation, but it is not significant at the 95% significance level.

Relationship with ENSO

Figure 8(b) presents the wavelet coherence between regional average CID and ENSO. The results show that around 1970 (at the scale of 2–4 years), CID and ENSO show a significant positive correlation, and around 1999 (at the scale of 1–3 years), there is a significant negative correlation. For other years of 1960–2017, CID and AO show an insignificant negative correlation.

Relationship with PDO

From the cross-wavelet transforms of area average CID and PDO shown in Figure 8(c), it could be seen that except for the significant positive correlation around 1975 (at the scale of 1–2 years), there is an insignificant negative correlation between CID and PDO for other years.

Relationship with SUNSPOT

Cross-wavelet analysis results (Figure 8(d)) indicate that CID and SUNSPOT show a significant positive correlation around 1982 (at the scale of 6–9 years), while for other years during 1960–2017, there is an insignificant relationship between CID and SUNSPOT.

The Tunxi station is selected for detailed analysis. Figure 9 indicates that the CID of Tunxi has a significant correlation with AO, ENSO, and SUNSPOT in some years. Specifically, CID and AO show a significant negative correlation around 1969 (at
the scale of 1–3 years) and 1990 (at the scale of 6–9 years), and ENSO shows a significant negative correlation around 1970 (at the scale of 2–4 years) and 1991 (at the scale of 6–12 years). There is a significant correlation with SUNSPOT around 1990, before 1990 the correlation is positive, and after 1990 it is negative. In addition, CID and PDO show a significant positive correlation around 1970.

Studies have shown that SUNSPOT is a potential factor that affects large-scale atmospheric circulation factors (Yamakawa et al. 2016; Huang et al. 2019; Zhang et al. 2019). Therefore, the cross-wavelet analysis is also performed between SUNSPOT, AO, ENSO, and PDO, and the results are shown in Figure 10. According to Figure 10 and Figure 8(d), it can be found that SUNSPOT is significantly correlated with CID, and it also has important effects on AO, ENSO, and PDO. In almost all years during 1960–2017, SUNSPOT has a significant correlation with AO, ENSO, and PDO. Given that CID has a significant positive correlation with AO, ENSO, and PDO in some years in the Yangtze River Delta, it can be inferred that SUNSPOT may cause CID changes indirectly. Finally, the changes would affect the water cycle process and cause variations in the spatial/temporal pattern of precipitation concentration (Huang et al. 2019).

DISCUSSIONS

Comparison between the results in the Yangtze River Delta and other areas

CID is an important index that reflects the temporal distribution of precipitation and is strongly related to regional flood risk management (Wang et al. 2019a, 2019b). Owing to the potential spatial heterogeneity of CID at large scale, results of this study would be compared with other regions. The CID values of the Yangtze River Delta range from 0.55 to 0.62, which is relatively close to Italy (0.43–0.63) (Caloiero 2014) but slightly lower than the United States (0.52–0.72) (Royé &

Figure 5 | Linear trends in the CID values for the four representative stations from 1960 to 2017. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2021.413.
Martin-Vide 2017) and Iran (0.59–0.73) (Alijani et al. 2008), and higher than Peru (0.42–0.58) (Zubieta et al. 2016). Monjo & Martin-Vide (2016) found that CID values range from 0.38 to 0.87, the results of other above-mentioned countries and the present study show that the value is within this range. The above results indicate that CID shows strong spatial heterogeneity in different regions, which may be related to climatic conditions, atmospheric circulation, and geomorphological factors (Zhang et al. 2009; Zheng et al. 2017).

In similar studies of mainland China, the difference of CID in different regions is also large, and results indicate that CID values of northeast and northwest (Lancang river basin) China are 0.60–0.77 and 0.58–0.73 (Shi et al. 2013; Wang et al. 2019a, 2019b), respectively, which are obviously higher than the values of the Yangtze River Delta. These findings also confirm the conclusion of the past studies, which reported that the CID values of northwest and northeast China are lower than those of the middle and lower reaches of the Yangtze River and southwest China (Zhang et al. 2009; Wang et al. 2019a, 2019b). That is to say, the spatial distribution of the CID values shows the opposite pattern with annual total precipitation in China. The causes are complicated and diverse, maybe the larger CID value in the northwest and northeast regions is because of the total annual precipitation in the region is lower, and the main rainfall amount concentrate on some few heavy precipitation days of flood season (Wang et al. 2019a, 2019b). However, in south China, due to the overall abundant water, the annual total precipitation is large with more rainy days, which offsets the unevenness of daily precipitation to some extent (Wang et al. 2019a, 2019b).

**Relationship with possible causes for different regions**

Studies have shown that causes or correlation relationships between precipitation concentration and potential driving forces are diverse (Zheng et al. 2017; Rahman & Islam 2019; Yang et al. 2020a, 2020b). Results of this study show that
CID and elevation show a slightly negative correlation. Royé & Martin-Vide (2017) reported that the precipitation concentration index is negatively correlated with altitude. Topography plays an important role in affecting precipitation characteristics and regional climate (Zheng et al. 2017). As for the mechanistic explanation of the negative correlation between altitude and CID, more in-depth and rigorous scientific studies are needed to investigate the inner mechanisms (Zheng et al. 2017).

This study also explores the relationship between the CID values and large-scale atmospheric circulation factors as well as SUNSPOTS. The results based on the wavelet analysis indicate that CID has significant correlations with the three large-scale atmospheric circulation factors in the Yangtze River Delta in some years during 1960–2017, and there are negative correlation with AO and positive correlation with ENSO and PDO. Results of this study are consistent with the conclusions of Huang et al. (2019), where the study area is located in the middle beach of Yangtze River. The above results indicate that the selected atmospheric circulation factors may be the important driving forces for CID variations. In addition, results reveal that the CID value has a significant correlation with SUNSPOT; furthermore, SUNSPOT is significantly correlated with large-scale atmospheric circulation factors in most years. This finding indicates that SUNSPOT is an important factor that affects CID, and may cause CID changes by large-scale atmospheric circulation factors indirectly. Some studies have shown that the effects of some large-scale atmospheric circulation factors are limited to some areas (Wang et al. 2017). For instance, Wang et al. (2019a, 2019b) reported that no significant correlations were detected between CID and large-scale atmospheric circulation indices, which indicate that the complex mechanisms are needed to be further studied.

Figure 7 | Scatter plot of CID versus elevation per decades. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2021.413.
CONCLUSION

In this study, the spatial and temporal variations of the daily precipitation concentration of the Yangtze River Delta are analyzed based on the Lorenz curve, and the relationships between daily precipitation concentration index and elevation, SUNSPOTS, as well as large-scale atmospheric circulations factors are explored during 1960 and 2017. The main conclusions are as follows:

(a) There is a non-significant upward trend for the daily precipitation concentration index in the Yangtze River Delta. The CID values of the study area range from 0.55 to 0.62 during 1960 and 2017, and 22 of 36 stations (accounting for 61%) show increasing trends, in which three of them are significant.

(b) The spatial distribution pattern of the daily precipitation concentration index is increasing from southwest to northeast in the Yangtze River Delta. Except for the 1970s, the CID values are high in the north (Jiangsu) and southeast area (Zhejiang) in all other decades from 1960 to 2017, while CID values of the other regions are in the middle.

(c) Large-scale atmospheric circulation factors and SUNSPOTS may be important factors that affect the daily precipitation concentration in the Yangtze River Delta. The regional average CID shows significant correlations with AO, ENSO and PDO in some years, indicating that they are potential driving forces of CID variations. The significant correlations between SUNSPOT and large-scale atmospheric circulation factors demonstrate that SUNSPOT is an indirect driving force changing the CID.

Figure 8 | Cross-wavelet transforms of area average CID and (a) AO, (b) ENSO, (c) PDO, and (d) SUNSPOT time series.
Figure 9 | Cross-wavelet transforms of CID of the Tunxi station (58531) and (a) AO, (b) ENSO, (c) PDO, and (d) SUNSPOT time series. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2021.413.

Figure 10 | Cross-wavelet transforms of SUNSPOT and (a) AO, (b) ENSO, and (c) PDO time series. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2021.413.
CID is an important reference index for regional flood prevention and water resource management. Analysis of spatiotemporal pattern variations of CID and their relationship with possible causes in the Yangtze River Delta provides scientific reference for decision-making of water security. In the future, further studies on the mechanism of precipitation concentration evolution and its impacts on flood risk should be proposed, which are the limitations of this study.

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DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

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