Trends in precipitation extremes and long-term memory of runoff records in Zhejiang, east China

YE TIAN[1,2], YUEPING XU[1], MARTIJN J. BOOIJ[2], QINGQING ZHANG[1] & SHENGJI LIN[1]

1 *Institute of Hydrology and Water Resources, Zhejiang University, Hangzhou, China*

2 *Department of Water Engineering and Management, University of Twente, Enschede, The Netherlands*
m.j.booij@utwente.nl

Abstract Extreme weather events have a huge impact on human beings and therefore it is of vital importance to investigate trends in relevant climatological and hydrological variables. In this study, precipitation and streamflow trends in Zhejiang Province in east China are analysed. Trends in annual and extreme precipitation for 18 meteorological stations (data periods 42 to 58 years) are studied using the Mann-Kendall test. Trends in the plum season (May–July) and typhoon season (August–October) are analysed separately as well. The scaling properties of streamflow for three hydrological stations (data periods 47 to 57 years) are determined using the detrended fluctuation analysis (DFA) method. Results show a positive trend in annual precipitation in the east and a negative one in the west. The major part of Zhejiang shows a positive trend in extreme precipitation, being more significant for 95% non-exceedence values than for 99% non-exceedence values. Precipitation intensity exhibits an upward trend in most areas and in both plum and typhoon seasons, especially in the coastal areas. The results of the DFA method show that long-term memory properties exist for one year in all three rivers. This time scale can be explained since the main source of the streamflow variation comes from climatic variability and the fact that annual streamflow cycles did not change.

Key words trends; precipitation; streamflow; Mann-Kendall; detrended fluctuation method; Zhejiang Province; China

INTRODUCTION

Extreme hydrological events related to precipitation and streamflow can cause large losses of human life and enormous economic and societal damage (Karl & Easterling, 1999). Climate change has made the situation even worse. Much work has been done to study how temperature, precipitation and streamflow are affected by climate change (e.g. Kunkel *et al*., 2003; Groisman *et al*., 2004; Vincent & Mekis, 2006; Bartholy & Pongracz, 2007; Khon *et al*., 2007; Tebaldi *et al*., 2007). For China, Zhai *et al*. (1999) reported a significant increase in the proportion of China affected by extremely high rainfall intensities. At the end of the 1970s and the beginning of the 1980s, there was an abrupt change of the number of days with extreme precipitation (Zhang *et al.*, 2008). The situation varies in different areas of China. Research to detect climate change has already been done in the middle and western parts of Guizhou province (Zhang *et al*., 2010a), Tarim River basin (Chen *et al*., 2006), Loess Plateau (Li *et al*., 2010) and northwestern Yangtze basin (Sua *et al*., 2008). However, no work has been done in the southeastern part of China, including Zhejiang Province.

The aim of this paper is to analysis the trends of extreme precipitation and streamflow in Zhejiang Province, China. Precipitation is unevenly distributed throughout the year, and about 70% of the annual precipitation occurs in the plum season (36%) and the typhoon season (34%). Therefore, precipitation trends of these two seasons are studied separately. Furthermore, in order to explore the scaling properties of streamflow in the study area, we applied the detrended fluctuation analysis method to three streamflow time series of different tributaries of the Qiantang River.

STUDY AREA AND DATA

The study area is Zhejiang Province (10.2×10^4 km^2) located in the southeast of China. Zhejiang is dominated by a subtropical monsoon climate, which is characterized by abundant precipitation and high temperatures in summer and dry and cold winters. The annual mean temperature is 15–18°C and the annual mean precipitation is 980–2000 mm, depending on the location within the study area. Generally, the precipitation amount is higher in the east and lower in the west. The main precipitation occurs in the plum season (from May to July) and typhoon season (from August to October). In the plum season, the southeast wind from the Pacific Ocean take warm humid air to the inland area, where it converges with cold air and rainfall is generated. In the typhoon season, typhoons with heavy rainstorms occur almost every year.

Daily precipitation data from 18 meteorological stations and daily streamflow data from three hydrological stations are used. The three hydrological stations Jinhua, Zhuji and Quzhou, are located in the Jinhua River, Puyang River and Qu River basins, respectively. These three rivers are important tributaries of the Qiantang River. These data were provided by the Meteorological Information Center of China and Zhejiang Hydrological Bureau. The daily precipitation data are available for 42 to 58 years, and the daily streamflow data for 47 to 57 years. The data were selected from a larger pool of stations in Zhejiang Province. Time series with several years missing or more than four missing observations per year were rejected. The selected series were quality controlled for inhomogeneity using the method presented by Wang (2003). Moreover, the results revealed that there are no breaking points and all time series used were consistent.

METHODS

Extreme precipitation indices

Seven extreme precipitation indices derived from daily precipitation were chosen from 27 temperature and precipitation indices defined by the Expert Team on Climate Change Detection and Indices (see Table 1). We have chosen these seven indices because we want to focus on the change in precipitation amount. An R-based program, RClimDexV3, developed at the Climate Research Branch of the Meteorological Service of Canada and available from a website (http://cccma.seos.uvic.ca/ETCCDI), was applied to calculate these seven extreme indices for the selected 18 meteorological stations.

Table 1 Definitions of extreme precipitation indices.

Indices	Description
SDII	Simple daily intensity index: average daily precipitation amount on wet days with precipitation > 1mm
P5MAX	Annual maximum consecutive 5-day precipitation
CDD	Maximum length of dry spell: maximum number of consecutive days with precipitation < 1 mm
CWD	Maximum length of wet spell: maximum number of consecutive days with precipitation ≥1 mm
PTOT	Annual total precipitation in wet days with precipitation > 1 mm
P95TOT	Annual total precipitation when precipitation > 95th percentile of precipitation on wet days (very wet days)
P99TOT	Annual total precipitation when precipitation > 99th percentile of precipitation on wet days (extremely wet days)

Mann-Kendall trend test

The non-parametric Mann-Kendall statistical test (Mann, 1945) is applied to determine whether long-term temporal trends exist for the seven indices in each of the 18 meteorological stations. The Mann–Kendall test is a rank-based procedure, which is less sensitive to outliers than parametric approaches, so it is widely used in hydrology and climatology (Chen *et al.*, 2007; Burn, 2008; Zhang *et al.*, 2010b). The magnitude of the trend is described by the Mann-Kendall estimator. The confidence level is at 95%.

Detrended fluctuation analysis

The detrended fluctuation analysis (DFA) method has been proposed to quantify the complexity of a non-stationary time series (Peng *et al.*, 1994). It is an important tool for the determination of fractal scaling properties and the detection of long-range correlations in noisy signals. In this study, the DFA method is applied to streamflow time series. First, a new integrated series $y(k)$ is obtained from the original series x_i ($i = 1, 2, \ldots N$) by the following equation:

$$y(k) = \sum_{i=1}^{k} (x_i - \bar{x}) \tag{1}$$

where $\bar{x}$ is the mean value of the original time series and N is the length of the time series.

Then the integrated time series is divided into N/s non-overlapping intervals with an equal length s. In each interval, the local trend is fitted by a linear line, the y-coordinate value of which is denoted by $y_s(k)$. Then, the local trend is subtracted from the integrated time series $y(k)$ in each interval and the variance is determined as:

$$F(\mathrm{s}) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} [y(k) - y_s(k)]^2} \tag{2}$$

The calculation is repeated over all interval sizes to provide a relationship between $F(s)$ and s, which can be described by $F(s) \propto s^{\alpha}$, where the slope of the line α indicates the scaling exponent. For a white noise signal, α equals 0.5. For $0.5 < \alpha < 1$, it indicates persistent long-range power-law correlations. In contrast, when $0 < \alpha < 0.5$, it presents anti-persistent correlation, which means that a large value is more likely to be followed by a small value. When $\alpha > 1$, correlations exist but cease to be a power-law exhibition.

RESULTS AND DISCUSSION

Trends in extreme precipitation indices

SDII Among the 18 stations, 11 stations are characterized by positive trends, and significant positive trends are observed in Yuhuan (0.05 mm/year), Dachendao (0.04 mm/year), Tianmushan (0.02 mm/year) and Shipu (0.02 mm/year). The eastern part of Zhejiang Province has experienced an increased daily precipitation amount on wet days, while in the inland area, unchanged or weak negative trends are observed.

P5MAX Among the 18 stations, 11 show increasing trends, most of which are located in the northern or coastal areas of the province. The increasing trends in Tianmushan and Dinghai are statistically significant at the 0.05 confidence level. The highest positive trend is found in Tianmushan Station with 1.3 mm/year, and the highest value for P5MAX is also found there with 603.7 mm in 1963. Seven stations show negative trends and are mainly located in a vast area in the southern or inland part of Zhejiang Province.

CDD Seven stations with negative trends are located in the northern region of Zhejiang Province (mainly coastal). Six stations in the southern region were dominated by a positive trend. Most inland stations did not show any trend. Significant negative trends are detected in Dinghai and Shengsi with –1.2 days per decade from 1955 to 2008, and –1.7 days per decade from 1959 to 2008, respectively. The decrease of the CDD index in Dinghai is related to the increasing extreme precipitation and such an increase is reflected in indices like P95TOT and P99TOT.

CWD A small area in the southeastern part of Zhejiang Province exhibited a decreasing trend, while the majority of the area (12 stations) did not show any trend. The strongest negative trends are detected in Dachendao, with –0.43 days per decade (significant). It is found that after 2003, none of the stations exceeded 11 days for this index, and the average number in Zhejiang Province dropped to only six days, indicating that the weather is getting drier in the southeast in recent years because of the decrease in CWD and the increase in CDD.

PTOT Most stations (12 out of 18 stations) are dominated by negative trends. Coastal stations in the northeast of Zhejiang Province, which have higher average precipitation amounts, are dominated by positive trends, and significant positive trends are detected in Dinghai, with 4.8 mm/year.

P95TOT Most stations have experienced very wet days each year. The highest precipitation in very wet days was recorded in Kocangshan in 1990 with 1757 mm. It is found that four out of five stations with more than 1000 mm precipitation on very wet days are located in the south-eastern area. Twelve out of 18 stations are dominated by positive trends for this index. All the coastal stations, except Wenzhou, are dominated by positive trends. The strongest and the only significant positive trends for P95TOT are found in Dinghai (coastal). Negative trends prevail in the inland areas. These results are similar to results reported in Christensen *et al.* (2007). These trends also imply that the spatial distribution of precipitation is becoming more uneven.

P99TOT Four stations, three along the coast and one in the mountain area, present positive trends. The largest positive trend is detected in Dinghai with 1.3 mm per year (significant). Only two stations show very weak negative trends. The other stations did not show obvious trends for extremely wet days.

Precipitation trends in plum and typhoon seasons

It has already been noted that the precipitation amount from May to October (plum and typhoon season) accounts for about 69.6% of the total amount. Therefore, precipitation trends are also estimated for all stations in the plum season and the typhoon season separately. Inverse distance weighting is used to determine the spatial distribution of the trends of precipitation and the number of rainy days in the plum and typhoon seasons. The results are shown in Fig. 1.

For the plum season, the strongest precipitation trends are found in the northwestern and southwestern inland region. The northwestern inland area shows a positive trend and the strongest upward trend in the plum season is 4.3 mm per year detected in Tianmushan from 1956 to 1997.

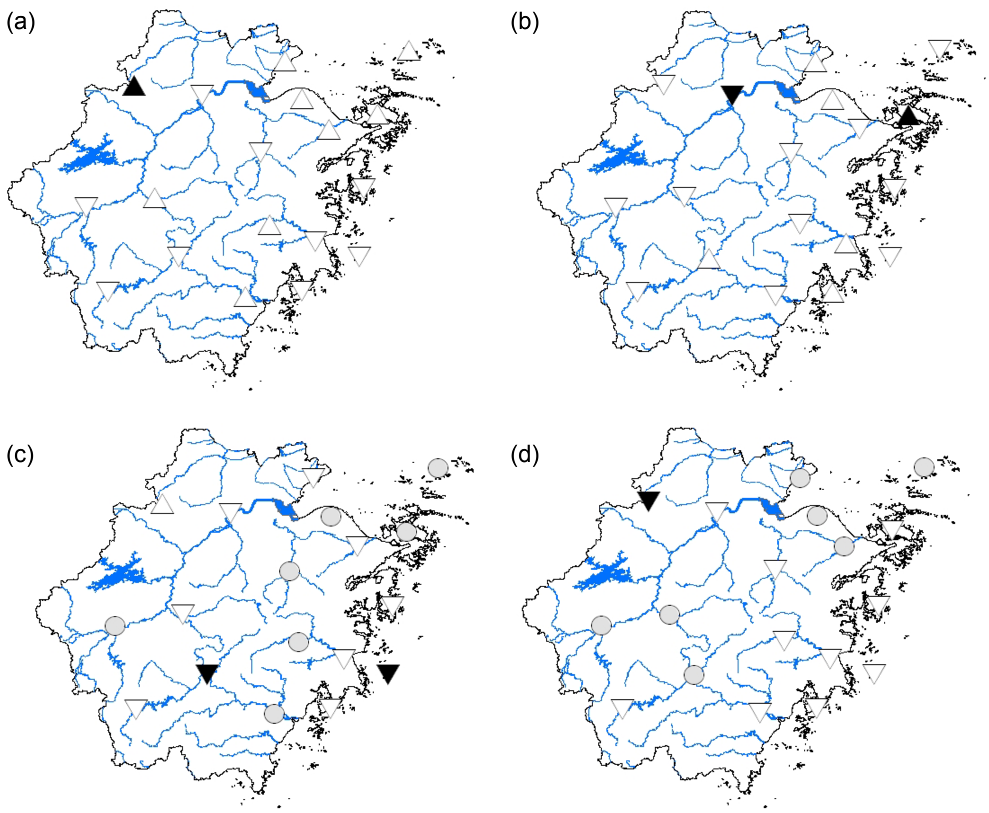

Fig. 1 (a) Precipitation trend in plum season; (b) trend of the number of precipitation days in plum season; (c) precipitation trend in typhoon season; (d) trend of the number of precipitation days in typhoon season. Here ○ represents no trend; Δ and ▲ represent positive and significant positive trends, respectively; ∇ and ▼ represent negative and significant negative trends, respectively.

Large areas in the southwestern part show a decline in the plum season precipitation and the strongest negative trend is found in Lishui, with –2.4 mm/year from 1953 to 2008. The eastern coastal areas, including Hongjia and Yuhuan, show a negative trend. For the number of precipitation days, there is a significant decrease in Lishui and Dachendao, with –0.1 days per year and –0.2 days per year, respectively. Ten stations show a negative trend and it only rains more often in Tianmushan. The spatial distribution of trends in precipitation amount and the number of precipitation days is very similar. A change in the precipitation intensity can be observed in the western part of Zhejiang Province. Although the number of precipitation days may decrease or does not change, the intensity of the precipitation has become higher in the plum season because of the increase in precipitation amount.

Streamflow trends

The log–log plots of $F(s)$ *versus* s of the streamflow series of the three river gauging stations in Zhejiang Province are shown in Fig. 2. The log–log plot of $F(s)$ *versus* s can be divided into two segments with different slopes at $\log(s) = 2.55$ ($s = 355$ days), $\log(s) = 2.58$ ($s = 380$ days) and $\log(s) = 2.52$ ($s = 331$ days) for Jinhua, Quzhou and Zhuji, respectively. The timing of the cross-over points is around a year. To determine the statistical properties of the fluctuations of runoff series, we compute the slope or α scaling exponent for smaller time scales. The α value of the runoff series of these three stations is 0.883 when $s < 355$ days, and 0.408 when $s > 355$ days for Jinhua station, 0.938 when $s < 380$ days and 0.419 when $s > 380$ days for Quzhou station, 0.855 when $s < 331$ days and 0.525 when $s > 331$ days for Zhuji station. The α value of these three stations is all larger than 0.5 and smaller than 1 when the time scale is around a year, which indicates persistence in the runoff series. Persistence means that if the runoff fluctuations have increased or decreased for a period, they tend to show an increase or decrease following a previous increase or decrease. For larger time scales than one year, anti-persistence, previous increase or decrease followed by a decrease or increase in values, respectively, can be observed. Within a year the runoff fluctuations are persistent, while at a larger time scale the slope is less than 0.5 in Jinhua and Quzhou, and close to 0.5 in Zhuji, which means the runoff fluctuations exhibit weak anti-persistence in Jinhua and Quzhou, and are more like white noise in Zhuji.

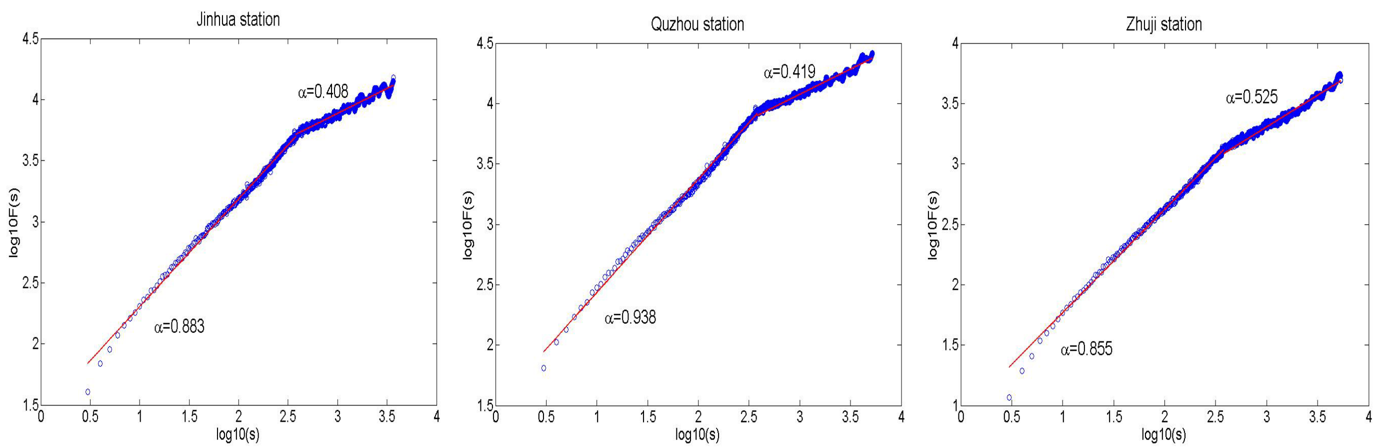

Fig. 2 Log–log plots of $F(s)$ *versus* s of Jinhua station, Quzhou station and Zhuji station.

CONCLUSIONS

Results show a positive trend in annual precipitation in the east and a negative one in the west from 1951 to 2008. The most obvious increase is found in Dinghai (in the east) with 4.8 mm/year and the largest decrease is found in Kuocangshan (in the west) with –3.9 mm/year. The major part of Zhejiang shows a positive trend in extreme precipitation, being more significant for 95% non-exceedence values than for 99% non-exceedence values. Precipitation intensity exhibits an upward trend in most areas and in both the plum and typhoon seasons, especially in the coastal areas. This is reflected in the increased precipitation amount and decreased number of wet days in those two seasons. The upward trends in the extreme indices shows that the eastern part is experiencing more and more extreme weather in summer, which is most likely to be caused by typhoons.

Results of the application of the detrended fluctuation analysis method indicate that the time scales for three stations are 355, 380 and 331 days, and the scaling exponents are all above 0.5 which indicate that the runoff fluctuations of all three rivers are characterized by a long-term memory of about one year. The crossovers in temporal correlation of the runoff may be explained by the fact that the streamflow amount is mainly controlled by the precipitation variation because of the unchanged annual cycle.

Acknowledgements The present study was sponsored by the Nature Science Foundation of China (Project 50809058), Major Project of Zhejiang Nature Science Foundation (Project Z5080048), and International Science & Technology Cooperation Program of China (2010DFA24320). We are very grateful to the Meteorological Information Center of China and Zhejiang Hydrological Bureau for providing all the data used in this study.

REFERENCES

Bartholy, J. & Pongracz, R. (2007) Regional analysis of extreme temperature and precipitation indices for the Carpathian Basin from 1946 to 2001. *Global Planet. Change* **57**(1-2), 83–95.

Burn, D. H. (2008) Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. *J. Hydrol.* **352**(1-2), 225–238.

Chen, Y. N., Takeuchi, K., Xu, C. C., Chen, Y. P. & Xu, Z. X. (2006) Regional climate change and its effects on river runoff in the Tarim Basin, China. *Hydrol Processes* **20**(10), 2207–2216.

Chen, H., Guo, S. L., Xu, C. Y. & Singh, V. P. (2007) Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. *J. Hydrol.* **344**(3-4), 171–184.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W. T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., Sarr, A. & Whetton, P. (2007) Regional climate projections. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller), 847–940. Cambridge University Press, Cambridge, UK.

Groisman, P. Y., Knight, R. W., Karl, T. R., Easterling, D. R., Sun, B. M. & Lawrimore, J. H. (2004) Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *J. Hydromet.* **5**(1), 64–85.

Karl, T. R. & Easterling, D. R. (1999) Climate extremes: Selected review and future research directions. *Climatic Change* **42**(1), 309–325.

Khon, V. C., Mokhov, I. I., Roeckner, E. & Semenov, V. A. (2007) Regional changes of precipitation characteristics in Northern Eurasia from simulations with global climate model. *Global Planet. Change* **57**(1-2), 118–123.

Kunkel, K. E., Easterling, D. R., Redmond, K. & Hubbard, K. (2003) Temporal variations of extreme precipitation events in the United States: 1895-2000. *Geophys. Res. Lett.* **30**(17), doi: 10.1029/2003gl018052.

Li, Z., Zheng, F. L., Liu, W. Z. & Flanagan, D. C. (2010) Spatial distribution and temporal trends of extreme temperature and precipitation events on the Loess Plateau of China during 1961-2007. *Quatern. Int.* **226**, 92–100.

Mann, H. B. (1945) Nonparametric tests against trend. *Econometrica* **13**, 245–259.

Peng, C. K., Buldyrev, S. V., Havlin, S., Simons. M., Stanley, H. E. & Goldberger, A. L. (1994) Mosaic organization of DNA nucleotides. *Phys. Rev. E* **49**(2), 168–-1689.

Sua, B., Gemmer, M. & Jiang, T. (2008) Spatial and temporal variation of extreme precipitation over the Yangtze River Basin. *Quatern. Int.* **186**, 22–31.

Tebaldi, C., Hayhoe, K., Arblaster, J. M. & Meehl, G. A. (2007) Going to the extremes - An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change* **82**(1-2), 233–234.

Vincent, L. A. & Mekis, E. (2006) Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Atmos. Ocean.* **44**(2), 177–193.

Wang, X. L. (2003) Comments on "Detection of undocumented changepoints: A revision of the two-phase regression model". *J. Climate* **16**(20), 3383–3385.

Zhai, P. M., Sun, A. J., Ren, F. M., Liu, X. N., Gao, B. & Zhang, Q. (1999) Changes of climate extremes in China. *Climatic Change* **42**(1), 203–218.

Zhang, D. Q., Feng, G. L. & Hu, J. G. (2008) Trend of extreme precipitation events over China in last 40 years. *Chinese Phys. B* **17**(2), 736–742.

Zhang, Q. A., Xu, C. Y., Zhang, Z. X., Chen, X. & Han, Z. Q. (2010a) Precipitation extremes in a karst region: a case study in the Guizhou province, southwest China. *Theor. Appl. Climatol.* **101**(1-2), 53–65.

Zhang, Q., Xu, C. Y., Tao, H., Jiang, T. & Chen, Y. D. (2010b) Climate changes and their impacts on water resources in the arid regions: a case study of the Tarim River basin, China. *Stoch. Environ. Res. Risk Assessm.* **24**(3), 349–358.