Methodology

According to [1], the concurrent extreme return period can be obtained through the copulas widely used in modeling the dependence between multiple variables [2, 3]. Assuming two variables X (e.g 1day cumulative precipitation) and Y (e.g. 30 days cumulative precipitation) with cumulative distribution functions $F_X(x) = Pr(X \le x)$ and $F_Y(y) = Pr(Y \le y)$, the copula (C) can be used to obtain their joint distribution function:

$$\begin{aligned} F(x,y) &= Pr(X \le x, Y \le y) \\ &= C(F_X(x), F_Y(y)) \end{aligned} \quad (1)$$

where $F(x,y)$ is the joint distribution function of X and Y.

From the joint distribution function F, the so-called joint survival distribution $\bar{F}$ and be obtained:

$F(x,y) = Pr(X \le x, Y \le y)$

$$\begin{aligned} \bar{F}(x,y) &= Pr(X > x, Y > y) \\ &= \hat{C}(1 - F_X(x), 1 - F_Y(y)) \end{aligned} \quad (2)$$

where $\hat{C}$ is the survival copula. Similar to the univariate return period analysis, the survival return period of X and Y is defined as follows:

$$\bar{k}_{x,y} = \frac{\mu}{1 - \bar{K}(t)} \quad (3)$$

where $\bar{k}_{x,y}$ is the survival Kendall's return period; $\mu > 0$ is the average interarrival time of X and Y ($\mu = 1$ in this study); and $\bar{K}$ is the Kendall's survival function associated with $\bar{F}$ defined as

$$\begin{aligned} \bar{K}(t) &= Pr(\bar{F}(X,Y) \ge t) \\ &= Pr(C(\bar{F}_X(x), \bar{F}_Y(y)) \ge t) \end{aligned} \quad (4)$$

In this study, Gaussian Copula model the dependence between Two-dimensional variables, the tau, par and p value of fitted Gaussian Copula for different cumulative precipitation are presented in Figure S6.

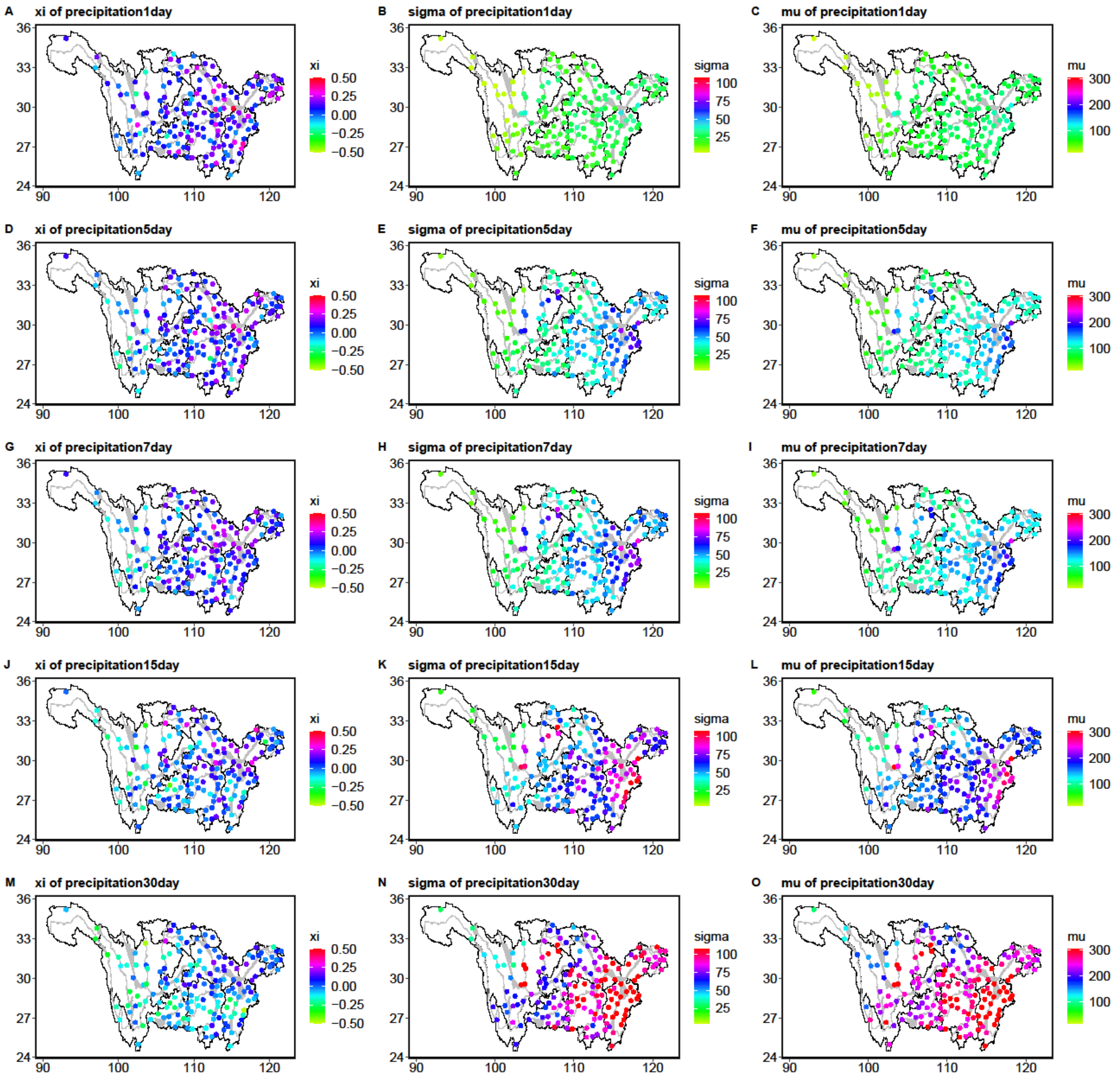

Figure S1. The fitted parameters of Generalized Extreme Value (GEV) distribution for different cumulative precipitation during 1960-2019.

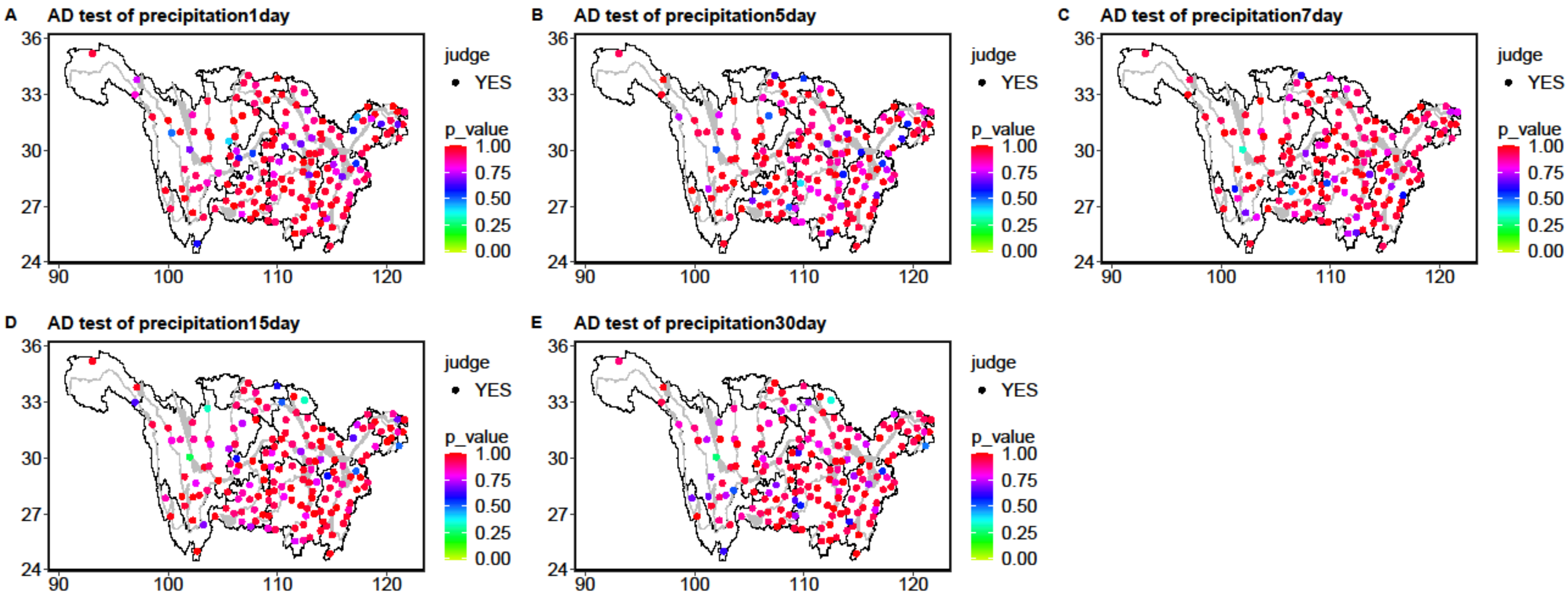

Figure S2. The AD test of fitted Generalized Extreme Value (GEV) distribution for different cumulative precipitation during 1960-2019. This result shows the fitted GEV in all stations pass the AD test.

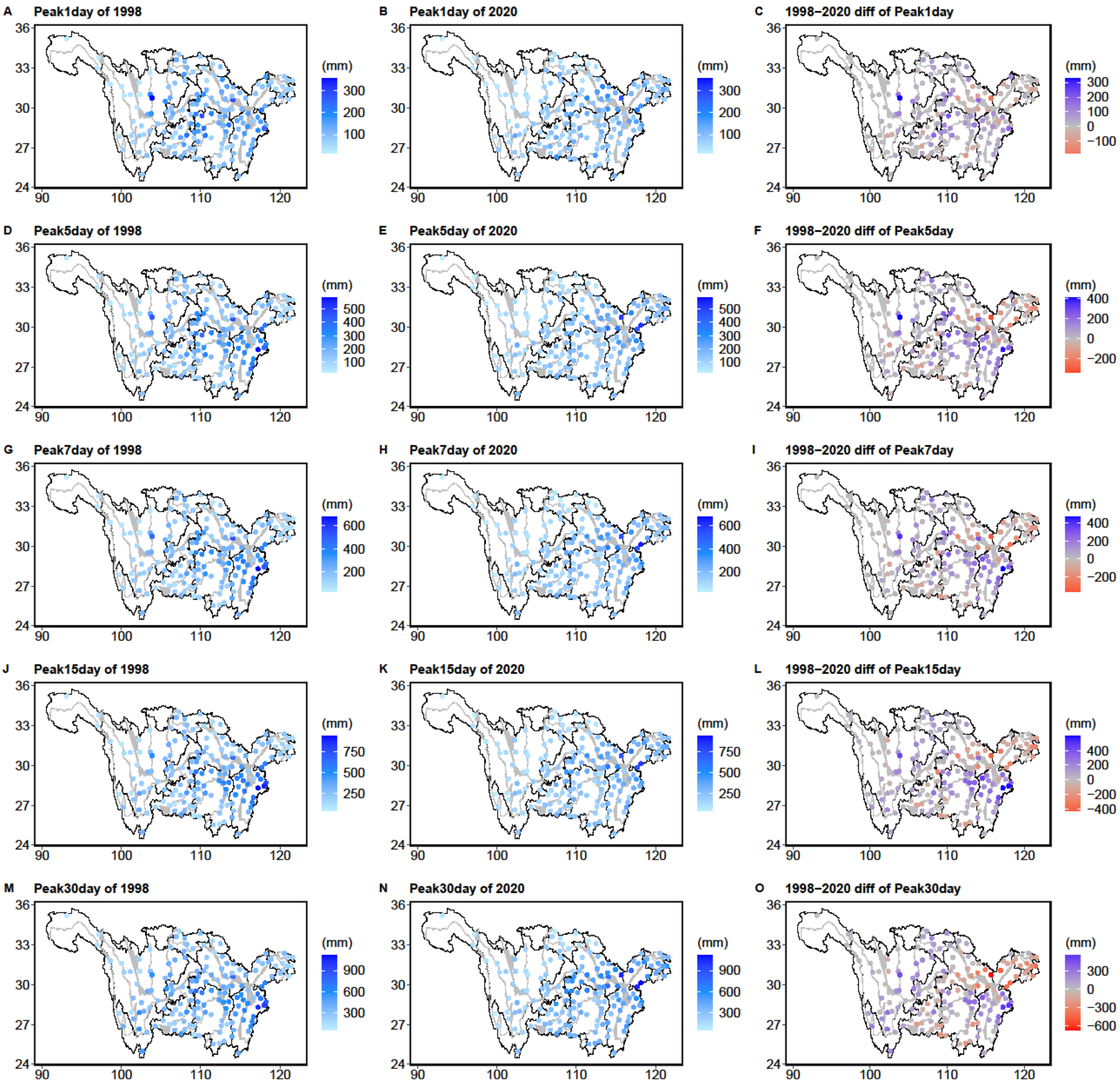

Figure S3. The spatial distribution of cumulative precipitation in 1998 and 2020. The third column present the different of cumulative precipitation. Blue and red show higher and lower precipitation in 2020 compared with 1998.

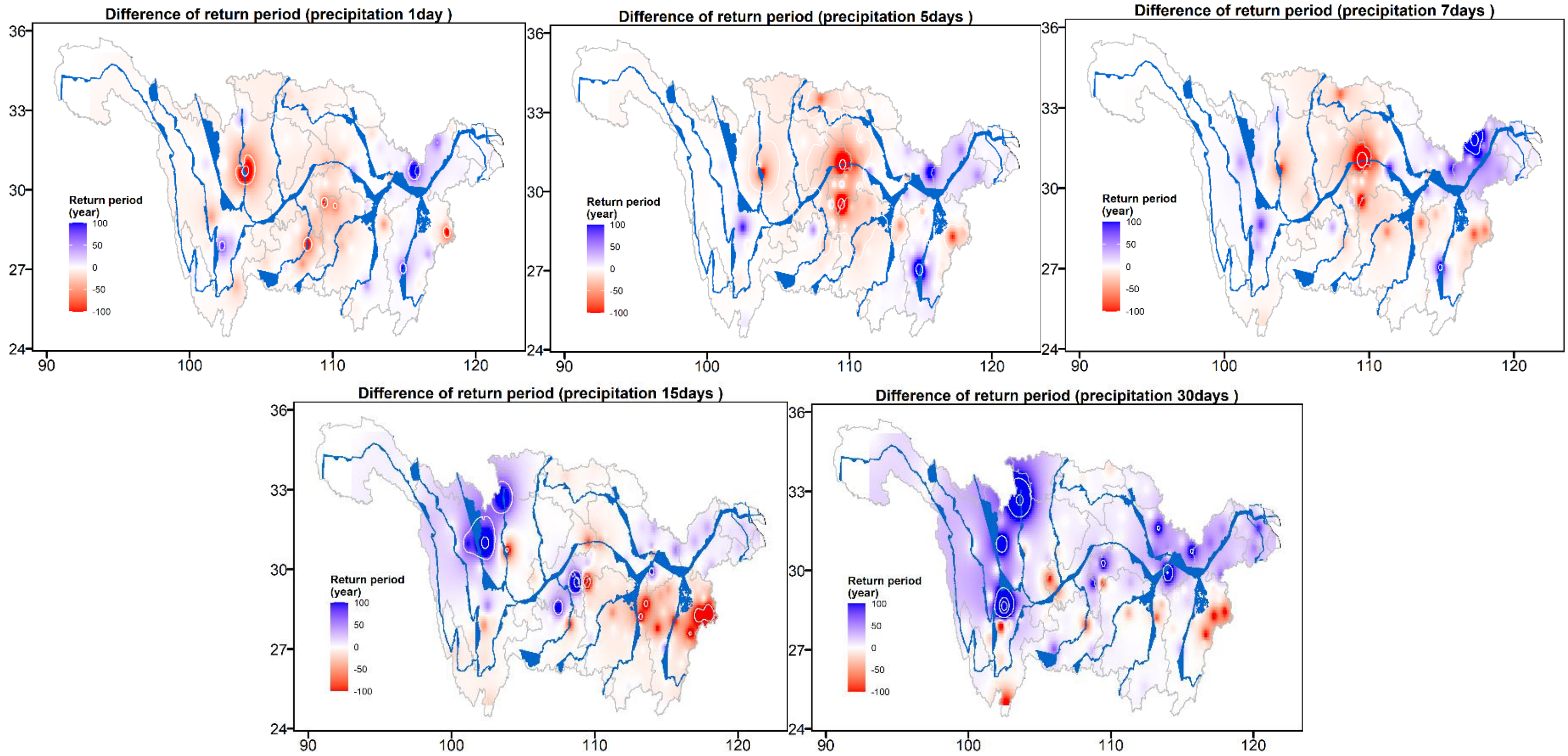

Figure S4. The spatial distribution of the RT difference in different cumulative days between 2020 and 1998. Blue and red show higher and lower precipitation in 2020 compared with 1998.

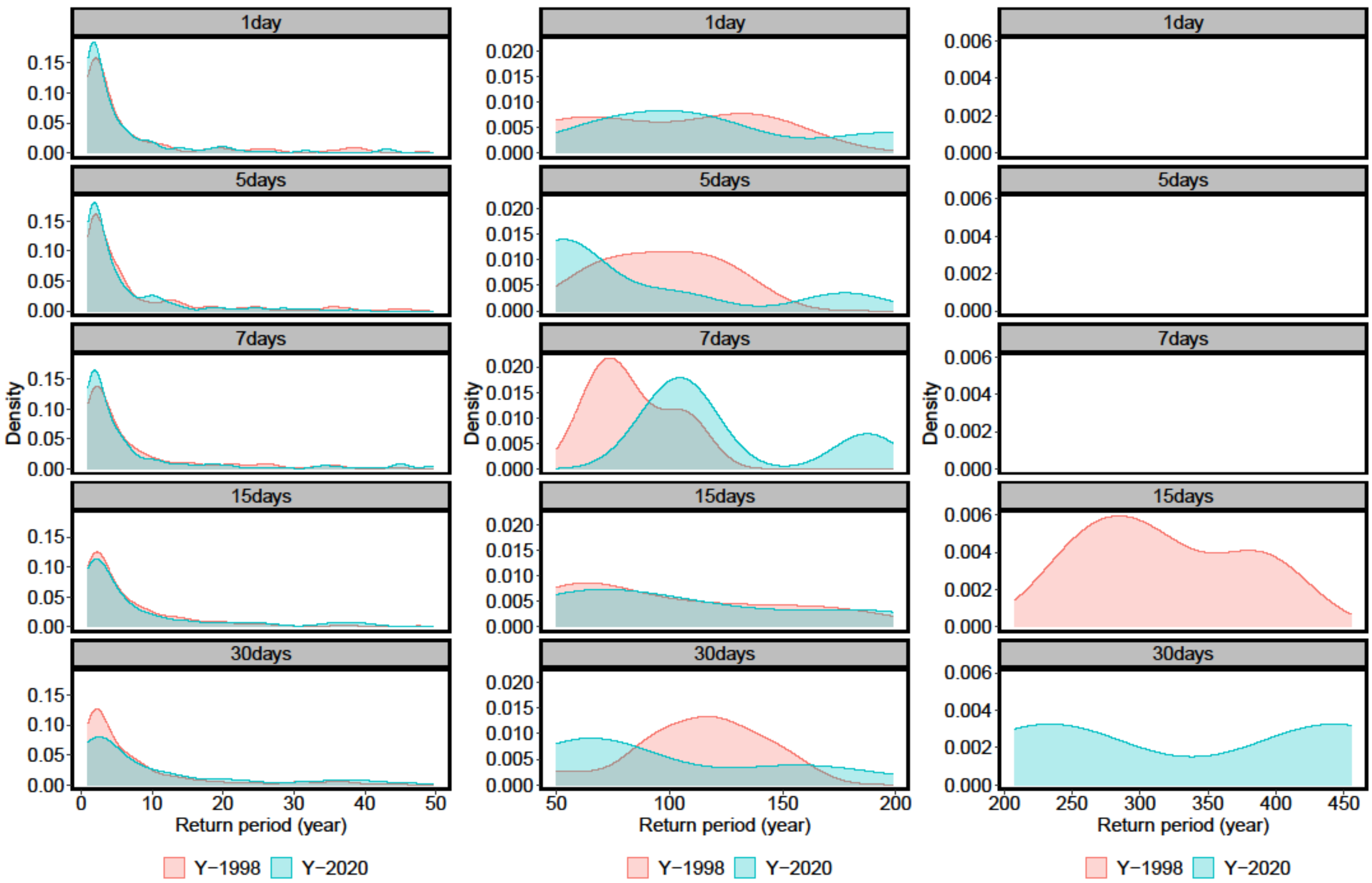

Figure S5. The probability density functions (PDFs) of return period for different cumulative precipitation in 1998 and 2020.

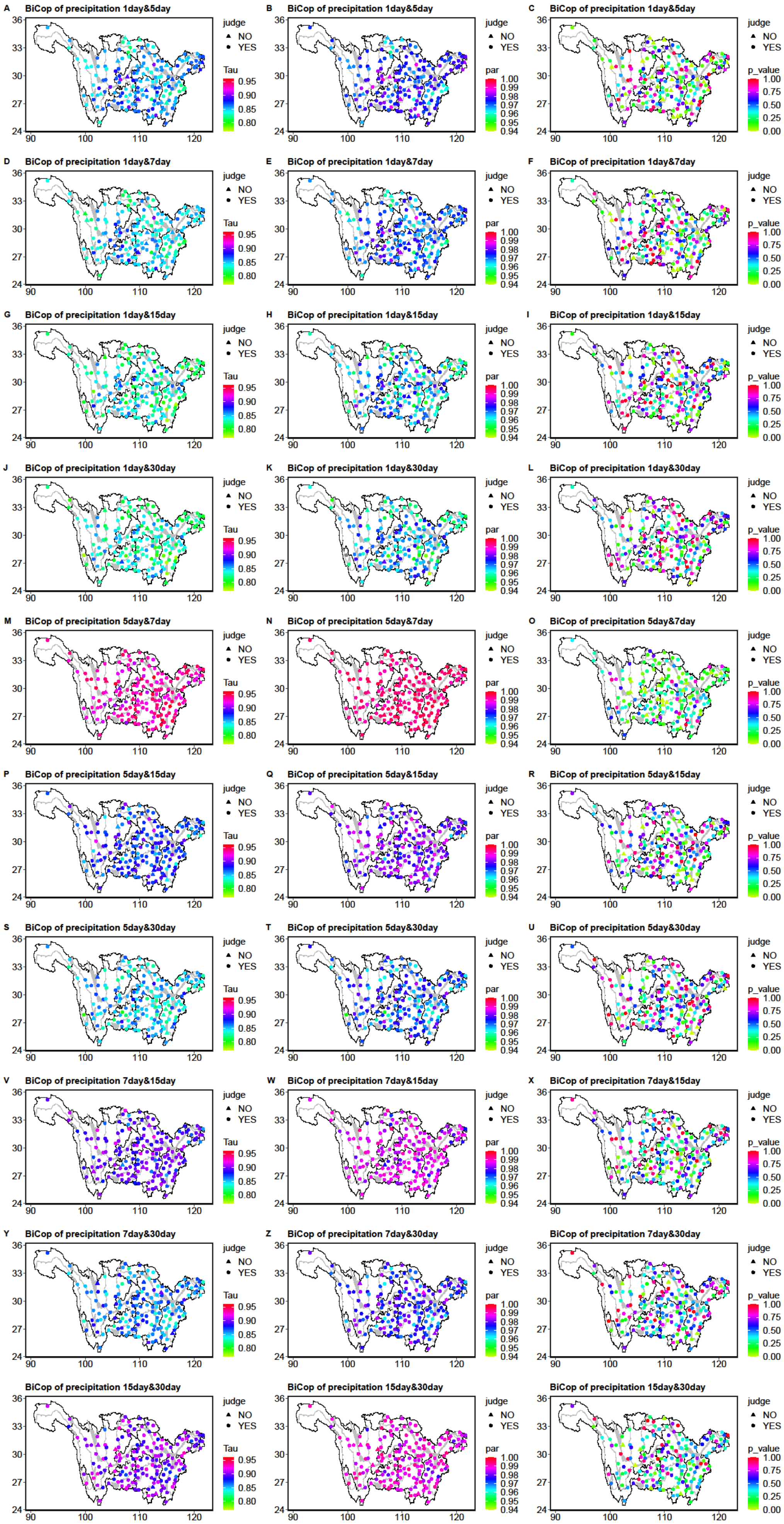

Figure S6. The tau, par and p value of fitted Bi-Copula for different cumulative precipitation during 1960-2019.

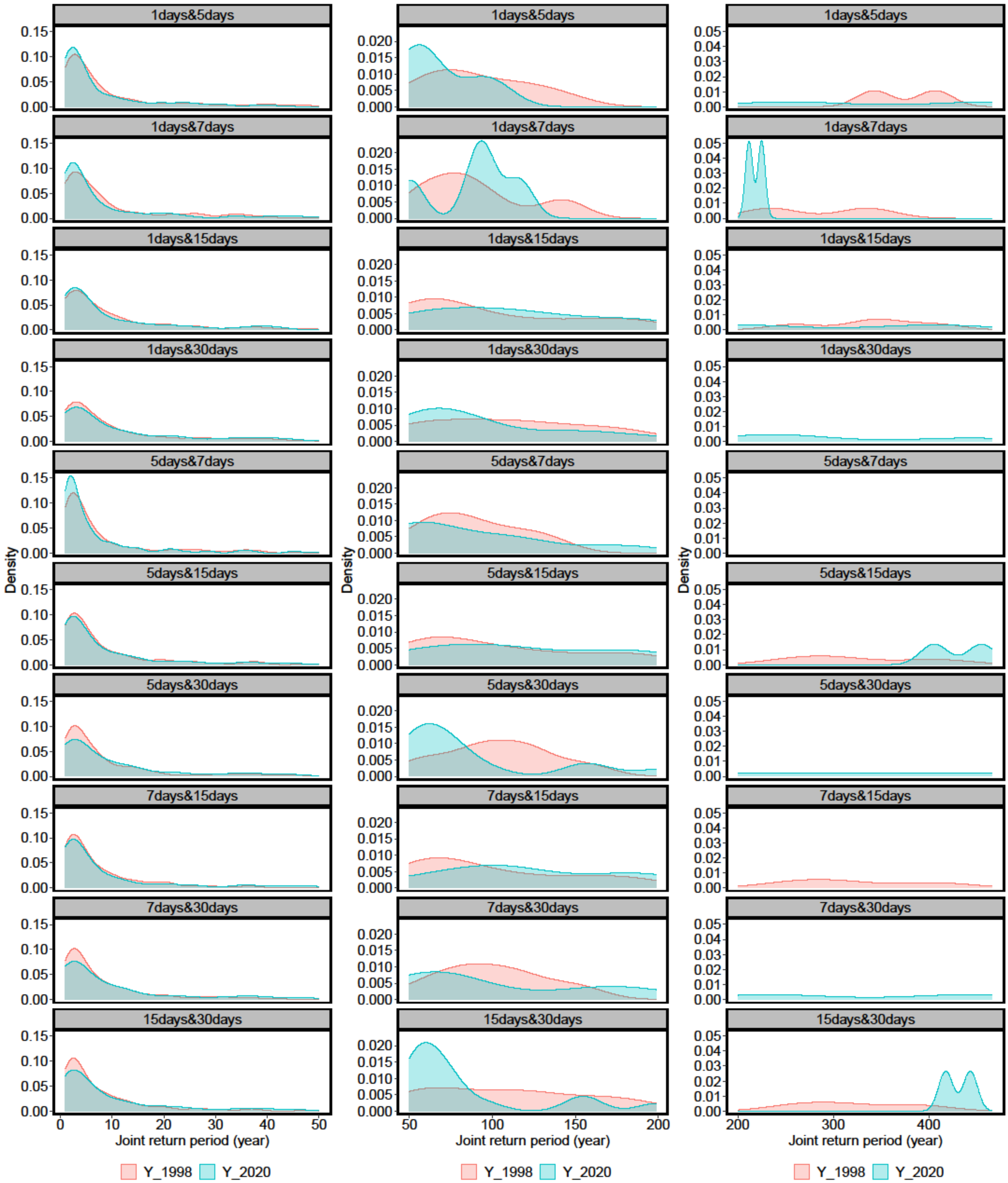

Figure S7. The probability density functions (PDFs) of joint return period for different cumulative precipitation in 1998 and 2020.

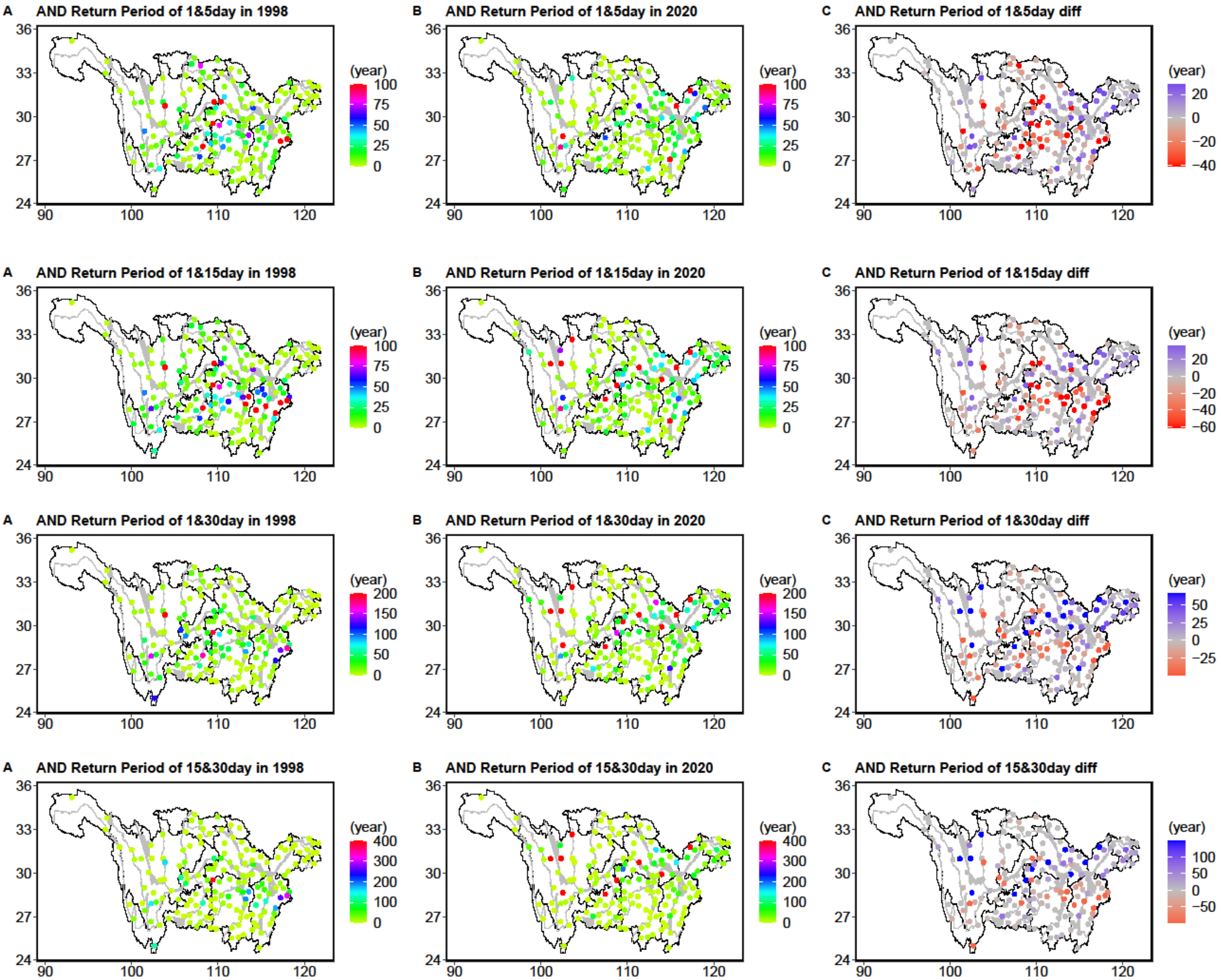

Figure S8. The station distribution of combined return period for different cumulative precipitation in 1998 and 2020.

1. AghaKouchak, A., et al., *Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought.* Geophysical Research Letters, 2014. **41**(24): p. 8847-8852.
2. Fan, Y., et al., *A factorial Bayesian copula framework for partitioning uncertainties in multivariate risk inference.* Environmental Research, 2020. **183**: p. 109215.
3. Fan, Y.R., et al., *Development of a copula-based particle filter (CopPF) approach for hydrologic data assimilation under consideration of parameter interdependence.* Water Resources Research, 2017. **53**(6): p. 4850-4875.