Atmospheric Research 264 (2021) 105838

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Risk changes of compound temperature and precipitation extremes in China under 1.5 °C and 2 °C global warming

Ailiyaer Aihaiti[a,b,c], Zhihong Jiang[a,*], Lianhua Zhu[a,c], Wei Li[a], Qinglong You[d,e]

[a] Key Laboratory of Meteorological Disaster, Ministry of Education (KLME), Joint International Research Laboratory of Climate and Environment Change (ILCEC), Nanjing University of Information Science & Technology, Nanjing 210044, China
[b] Institute of Desert Meteorology, China Meteorological Administration, Urumqi 830002, China
[c] School of Mathematics and Statistics, Nanjing University of Information Science & Technology, Nanjing 210044, China
[d] Department of Atmospheric and Oceanic Sciences, Institute of Atmospheric Sciences, Fudan University, Room 5002-1, Environmental Science Building, No.2005 Songhu Road, Yangpu, Shanghai 200438, China
[e] Innovation Center of Ocean and Atmosphere System, Zhuhai, Fudan Innovation Research Institute, Zhuhai 518057, China

ARTICLE INFO

Keywords:
Global warming
Compound events
Risk changes
Warm/dry event
Warm/wet event

ABSTRACT

Based on the simulated temperature and precipitation from CMIP6 models, the joint distribution characteristics of summer temperature and precipitation in China are described in the Copula approach. The occurrence risk of compound extremes (i.e., warm/dry, and warm/wet events) and corresponding univariate events (i.e., warm, wet, and dry events) in historical period are compared; and the risk changes of compound extremes are discussed under global warming 1.5 °C and 2 °C. Results show that: 1) the Copula approach can describe the joint probability distribution of summer temperature and precipitation in observation and model simulations in most parts of China except for the Qinghai-Tibet Plateau; 2) The average risk of warm and wet events in China increases by 2.3 and 1.16 times under 1.5 °C warming respectively, increases by 2.83 and 1.29 times under 2 °C warming respectively while the risk of dry events decreases in most parts of China; 3) The average of warm/wet events in China increases by 5.48 and 10.01 times under 1.5 °C and 2 °C warming, respectively. Regions over Northern China and South China experience the most increased risk about more than 8 times. The warm/dry events show less increase magnitude with 1.82 and 2.04 times under two warming climates, respectively. The highest increase in risk is mainly located in Northern China. At an additional 0.5 °C warming from 1.5 °C to 2 °C, the regional average risk of warm/dry and warm/wet events increases by 1.40 and 2.74 times, respectively. In most areas, the risk of warm/wet events increases significantly and are greater than that of warm/dry events. This indicates that controlling global warming up to 1.5 °C can avoid more intense warm/dry and warm/wet events. Our work highlights that the risk of compound extremes may be underestimated if we only consider the univariate events.

1. Introduction

Extreme events in the world are one of the most destructive natural disasters, causing serious economic losses almost every year. Under the background of anthropogenic global warming, extreme climate events exhibit a significant increase over different regions across the world (Zhai and Pan, 2003; Zhai et al., 2005; Shi et al., 2020). Compared to a single extreme weather and climate event, compound extremes defined by two or more extreme events occurring simultaneously or successively may amplify the impact on the environment and human society (AghaKouchak et al., 2014, 2020; Orth et al., 2016).

Extreme weather and climate events such as hot, drought and flood are closely related to temperature and precipitation (Hao et al., 2018a, 2018b; De Luca et al., 2020). The simulation and projection of temperature and precipitation compound extremes have been widely analyzed in different regions around the world. Hao et al. (2013) studied compound extremes of different combinations of precipitation and temperature in historical periods and found that the occurrence of warm/dry and warm/wet events increased significantly on the global scale. Zscheischler et al. (2017) found that univariate events are related to each other and that assessment based on univariate analysis may underestimate the risks of compound extremes. Vogel et al. (2020)

* Corresponding author.
E-mail address: zhjiang@nuist.edu.cn (Z. Jiang).

https://doi.org/10.1016/j.atmosres.2021.105838
Received 14 April 2021; Received in revised form 26 August 2021; Accepted 26 August 2021
Available online 28 August 2021
0169-8095/

analyzed the future risk of different type of compound extremes under the global warming of 1.5 °C to 4 °C based on the 6th phase of the Coupled Model Intercomparison Project (CMIP6) models. They found that, with the increase of global warming, the hot/drought events occur more frequently than other type of compound extremes. These studies show that with global warming, the risk of warm/dry and warm/wet events increases significantly in recent years and in future periods.

Previous researches related to the extreme temperature and extreme precipitation events in China focus mainly on univariate analysis (Shi et al., 2018; Li et al., 2020). During the historical period, the extreme precipitation events in western China, the middle and lower reaches of the Yangtze River, southwestern and some coastal areas of southern China exhibit an increasing trend, while the northern and southwestern regions witnessed a decreasing trend. As for the extreme temperature, the increase trend of the frequency and intensity of extreme hot events have been reported across many regions over China, especially in northern and western China (Zhai et al., 2005; He and Zhai, 2018; Dong et al., 2018; Qian et al., 2019; Sun et al., 2019). Under 1.5 °C and 2 °C warming, extreme hot and heavy precipitation events in most regions of China, especially in northern part of China, are projected to increase (Li et al., 2018a, 2018b, 2018c; Wu et al., 2020). In addition, the return period of the regional averaged extreme hot and extreme precipitation events are projected to shorten under different warming levels (Li et al., 2018a, 2018b, 2018c; Sun et al., 2019). Recently, the academic attention on the changes in the compound extremes in China (i.e., warm/wet, warm/dry, cold/wet and cold/dry events) has been increasingly attracted by the researchers. For example, Wu et al. (2019) explored the seasonal changes in the warm/wet, warm/dry, cold/wet and cold/dry events from 1961 to 2014, finding that the frequency of warm/wet and warm/dry events increased significantly over period from 1988 to 2014 compared to the period from 1961 to 1987. However, the frequency in the cold/wet and cold/dry events showed decreased trend. Qian et al. (2014) further analyzed wet/cold events during 1951–2011 and found that more frequent wet/cold events was observed over southern China, especially in the eastern part of southwest China and southern China.

Although there is much work worth investigation about the future changes in the compound extremes in China, there is still lack of studies about the future changes in the risks of warm/dry and warm/wet events under different global warming climate. This paper focuses mainly on the future risk changes in the warm/dry and warm/wet events under 1.5 °C and 2 °C climate using CMIP6 models. The definition of compound extremes is conducted by the Couple method, which is used to characterize the joint distribution of temperature and precipitation.

This paper is structured as follows. Section 2 introduces observations, model data and the definition of compound extremes. Section 3 analyzes the observed changes in univariate events and compound extremes, explores the risk changes of univariate events and compound extremes under different warming levels. Finally, Section 4 is the conclusion and discussion.

2. Data and methods

2.1. Data

In this paper, we used a high resolution (0.25° x 0.25°) of daily temperature and precipitation data covering 1961–2015 from CN05.1 (Wu and Gao, 2013). The daily precipitation and temperature data from 12 CMIP6 models based on historical (1986–2005) and Shared Socioeconomic Pathway 245 (ssp245) simulations (2015–2100) are used (Zhu et al., 2020). Then, six model's ensemble is selected which can well simulate the correlation between temperature and precipitation. These six models are BCC-CSM2-MR, CNRM-CM6–1, CNRM-ESM2–1, GFDL-CM4, GFDL-ESM4 and FGOALS-g3, respectively. Surface temperature in both historical and future scenarios are used to estimate the timing when global reaches the two warming climate thresholds. The time series of global mean surface temperature are smoothed by 21-year running mean, then the 1.5 °C and 2 °C time periods are defined as two 10-year periods around the first year that the temperature rise is 1.5 °C and 2 °C relative to pre-industrial period (1861–1900) for each model (Table 1) (). Due to the inconsistency of resolution between the observation and simulation, all models and observations are interpolated into the 1° × 1° resolution to facilitate comparison.

2.2. Compound extremes

There are many definitions of the compound precipitation and temperature extremes. As for the univariate event, the warm event is defined as the temperature over the 75th percentile. The wet and drought events are defined as the precipitation over the 75th percentile and below the 25th percentile, respectively. As for the compound extremes, the warm/wet event is defined as the temperature and precipitation simultaneous over the 75th percentile. Similarly, the warm/dry event is regarded when temperature over the 75th percentile and precipitation below the 25th percentile occur simultaneously. It should be noted that the precipitation series is multiplied by minus 1 when considering dry events and warm/dry events, which means that all the events are defined as the precipitation and temperature are over the 75th percentile.

Two different approaches were used to investigate the compound extreme event: (1) A simple count of the days with compound extremes (warm/wet and warm/dry); (2) Develops copula families to model the multivariate dependence of temperature and precipitation (Zscheischler et al., 2017).

The marginal distribution function of temperature and precipitation adopt empirical Gringorten plotting formula to avoid assumptions of parameters distribution forms. For the two random variables X (temperature) and Y (precipitation) whose marginal distributions is defined as $U = F_X(x) = \Pr(X \le x)$and $V = F_Y(y) = \Pr(Y \le y)$respectively. The joint distribution is represented by Copula C (Hao et al., 2018a, 2018b):

$$F(x,y) = Pr(X \le x, Y \le y) = C(F_X(x), F_Y(y); \theta) \tag{1}$$

where, θ is the parameter of the copula function, and C is the joint distribution function of two random variable X and Y. For the warm/dry events, $V = F_{-Y}(-y) = \Pr(-Y \le -y)$ and $F(x,-y) = \Pr(X \le x, -Y \le -y) = C(F_X(x), F_{-Y}(-y); \theta)$. Therefore, the joint probability of a compound extremes in which the temperature and precipitation exceed the 75th percentile (i.e., $u = v = 0.75$) simultaneously can be calculated (Salvadori et al., 2011, 2013):

$$p = Pr(U > u \cap V > v) = 1 - u - v + C(u,v) \tag{2}$$

Furthermore, this paper uses probability ratio (PR) to explore the future risk changes of univariate and compound extremes. The PR of univariate event is expressed as:

$$PR = \frac{p_1}{p_0} \tag{3}$$

Among them,$p_0$is the probability of a given univariate (warm, wet, dry) event occurring in the reference period, and$p_1$is the probability of this univariate event occurring under different warming backgrounds.

Table 1
Information of CMIP6 climate model and the 20-year time slices when global warming reaches to 1.5 °C and 2 °C relative to pre-industrial period under ssp245 scenario.

Model name	Countries	Resolution	1.5 °C	2.0 °C
BCC-CSM2-MR	China	1.125° × 1.125°	[2027, 2047]	[2049, 2069]
CNRM-CM6–1	French	1.4° × 1.4°	[2020, 2040]	[2037, 2057]
CNRM-ESM2–1	French	1.4° × 1.4°	[2027, 2047]	[2045, 2065]
GFDL-CM4	USA	1° × 1.25°	[2021, 2041]	[2039, 2059]
GFDL-ESM4	USA	1° × 1.25°	[2037, 2057]	[2064, 2084]
FGOALS-g3	China	2° × 2°	[2021, 2041]	[2053, 2073]

The PR of compound extreme, calculated based on formula (2) and formula (3), can be expressed as:

$$PR = \frac{1-(1-p_1)-(1-p_2)+C(1-p_1,1-p_2)}{1-(1-p_0)-(1-p_0)+C(1-p_0,1-p_0)} \tag{4}$$

where,$p_0$is the probability of univariate event occurring in the reference period, which is the same for the compound extremes. In our study,$p_0$is 0.75th percentile for temperature and precipitation.$p_1$and$p_2$are the probability of extreme temperature and precipitation under different warming climate, respectively. That is, $1-(1-p_0)-(1-p_0)+C(1-p_0,1-p_0)$ represents the probability of warm/wet (or warm/dry) event occurring in the base period, and $1-(1-p_1)-(1-p_2)+C(1-p_1,1-p_2)$ represents the probability of occurrence of this compound extreme event under different warming backgrounds.

There are varieties of copula familiar used for different dependence structure of random variable. In order to describe the dependence structure between temperature and precipitation, this paper uses four Archimedean copulas and independent copula. Archimedean copulas is expressed as:

$$C:[0,1]^2\rightarrow[0,1], C(u,v):=\varphi^{[-1]}(\varphi(u)+\varphi(v)) \tag{5}$$

Four copula families were used to construct the joint distribution in this study:

$$Frank\ copula:\varphi(t)=-ln\left(\frac{e^{-\theta t}-1}{e^{-t}-1}\right),\theta>0 \tag{6}$$

$$Clayton\ copula:\varphi(t)=\frac{1}{\theta}\left(t^{-\theta}-1\right),\theta>0 \tag{7}$$

$$Gumbel\ copula:\varphi(t)=(-lnt)^{\theta},\theta>1 \tag{8}$$

$$Joe\ copula:\varphi(t)=-ln\left(1\text{-}(1\text{-t})^{\theta}\right),\theta>1 \tag{9}$$

The Archimedean copulas model parameters are estimated by the L-moment method based on Kendall's tau inversion (Kojadinovic and Yan, 2010). The AIC criterion is used to select the best copula model (Zscheischler et al., 2017).

3. Results

3.1. Observation of univariate and compound extremes

The dependence structures between temperature and precipitation are needed before analyzing the compound extremes. Fig. 1 shows the spatial distribution of the Kendall rank correlation coefficients between observed temperature and precipitation in historical period. A negative correlation between precipitation temperature is observed in most parts of China with the value of Kendall's rank correlation coefficient above 0.3 over Eastern, Southern and Western Northwest regions. This indicates that the warm (cold) temperature usually occurs simultaneously with the little (heavy) precipitation. Therefore, warm/dry, and cold/wet events are the main compound extremes in most areas of China from 1961 to 2015. There is a positive correlation between temperature and precipitation over the Tibetan Plateau, but the limitation of observation data in this region reduces the credibility of the results.

In order to further explain the relationship between temperature and precipitation in historical period, Fig. 2 gives scatter plot of observed temperature and precipitation for three example grid points (lon = 118.75°E, 113.75°E, 98.75°E, lat = 28.75°N, 41.75°N, 39.75°N). It can be seen that the warm, wet and dry events occurred 14 times from 1961 to 2015, while warm/dry and warm/wet events occurred less than 10 times (the upper right corner of Fig. 2a-f). In addition, the difference in the probability of univariate events and compound extremes are displayed in Fig. 2(g-l). The goodness of fit of copulas is also evaluated in Fig. 2 (g-l), and the copula model can well describe the joint distribution

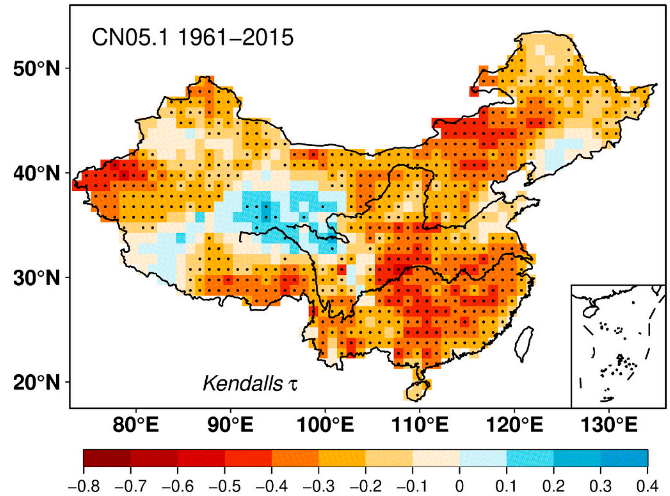

Fig. 1. Spatial distribution of Kendall rank correlation coefficients between observed temperature and precipitation during 1961–2015. The dotted area indicates that the Kendall rank correlation coefficient is significantly at 0.1 level basted on correlation test.

of temperature and precipitation.

Table 2 shows the recurrence periods of 8 warm/dry events, 2 warm/wet events and corresponding the univariate events for the first example grid point (Fig. 2a, d; lon = 118.75°E, lat = 28.75°N) in the 1961–2015. The recurrence period of these univariate warm, wet and dry events ranges from 4 to 55, 4.58 to 7.86 and 4.23 to 27.5 years, respectively. Among these, the warm event occurring in 1971 is the longest recurrence period (once in 55 years), the longest return period of dry and wet event is in 1978 (once in 27.5 years) and in 2011 (once in 7.86 years), respectively. However, the recurrence periods of warm/dry and warm/wet events are even up to 15.36–166.71 years and 63.88–73.42 years respectively. The warm/dry event in 1971 was the rarest event (recurrence period exceeded 150 years), while the warm/dry events are not rare. This indicates that if we focus only on the univariate event, the risk caused by the compound extremes may be largely underestimated.

3.2. Risk change analysis of compound extremes

3.2.1. Future risk changes of warm, wet, and dry events

Based on the historical period, focusing only on the univariate event may underestimates the risk of compound extremes. Therefore, the model simulations under future scenario is used to verify this by comparing the risk of univariate events and compound extremes. Firstly, the risk changes of univariate events under different warming backgrounds were analyzed. Fig. 3 shows the spatial distribution of PR changes of warm, wet, and dry events in the historical period (1986–2005) under 1.5 °C and 2 °Cwarming. The regional averaged risks of warm, wet, and dry events will increase by 2.30, 1.16 and 0.86 times under 1.5 °C warming respectively, while increase by 2.83, 1.29 and 0.82 times under 2 °C warming respectively. Northeast and Northwest China will receive the most increase in the risk of warm event (2–4 times). For 1.5 °C warming climate, the most increase risk of wet event is mainly located over eastern China and central northwest China with the risk increasing by 1.25–1.75 times, while the future risk exhibits decrease in the south of the middle reaches of the Yellow River, the north of the middle reaches of the Yangtze River and the west of the northwest. Future risk of dry events will be reduced in most parts of China (PR < 1). For 2 °C warming climate, the risk of warm events in Northeast and Northwest China will increase by 3 to 4 times. At the same time, the areas with the increase risk of wet events will be further expanded with the risk increase by 1.25 to 2 times. The future risk of warm and wet events over Northeast and Northwest China will increase

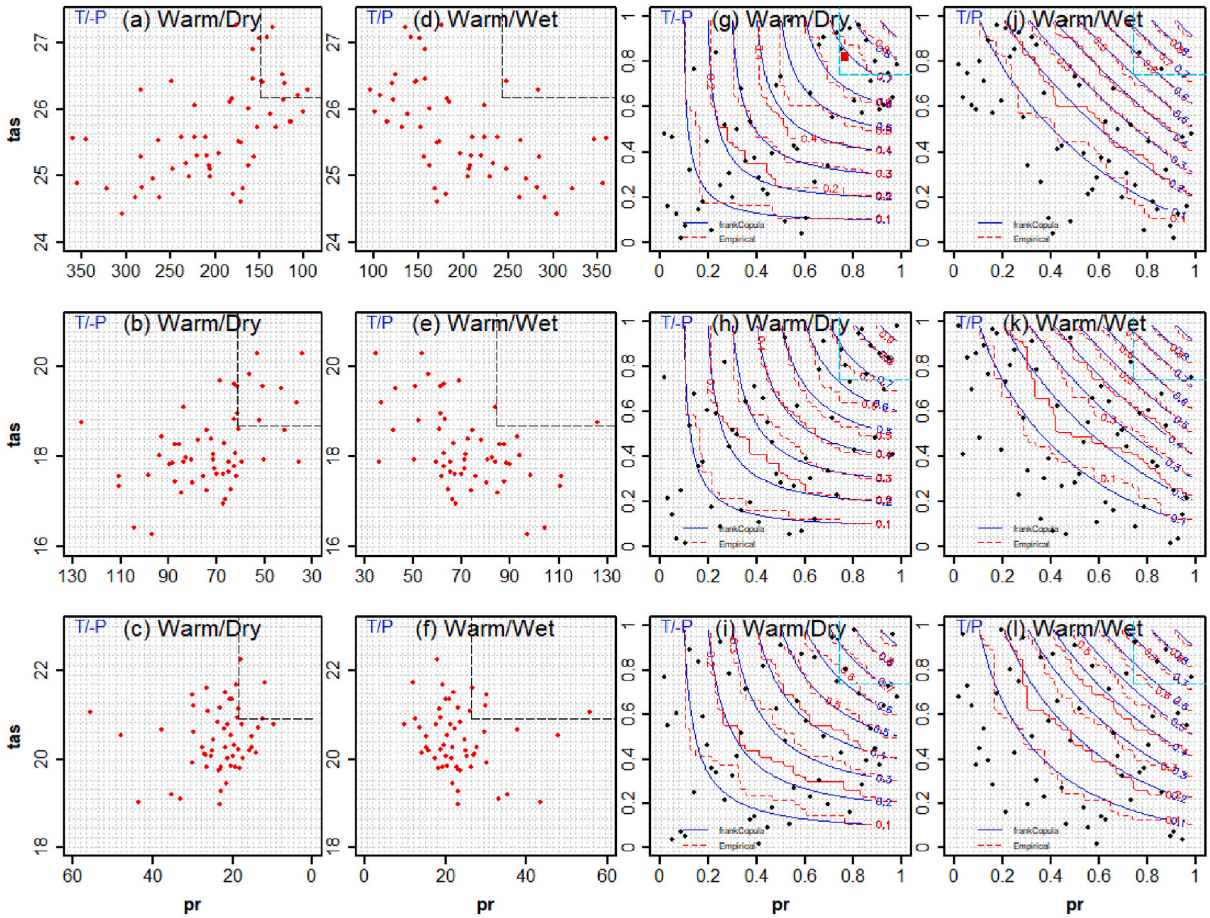

Fig. 2. The original scatter plots (a-f) and standardized scatter plots (g-l) between observed temperature and precipitation at a given grid point (lon = 118.75°E, 113.75°E, 98.75°E, lat = 28.75°N, 41.75°N, 39.75°N) during 1961–2015. The blue solid and red dotted line represent the joint probability distributions of temperature and precipitation based on frankCopula and empirical distribution, respectively. The scatter plots in rows 1–3 corresponds to three grid points, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The recurrence periods of 8 warm/dry events and 2 warm/wet events and their corresponding univariate events in a given grid point from 1961 to 2015.

Year	Warm event	Dry event	Warm/dry event
1971	55.00	6.11	166.71
1978	4.23	27.50	61.06
1988	6.11	4.58	15.36
1990	7.86	4.23	18.12
1991	5.00	–	–
2003	27.50	5.00	70.44
2005	5.50	11.00	31.41
2007	11.00	7.86	43.45

Year	Warm event	Wet events	Warm/wet event
1994	6.88	4.58	63.88
2011	4.58	7.86	73.42

Note: The marginal distribution of temperature and precipitation in this paper adopts the empirical distribution. The precipitation in 1991 is the minimum value across the period, that is, the occurrence of dry event is inevitable (occurrence probability is 1), so its recurrence period is not considered.

and the risk of dry events in most of China will decease under the continued warming climate.

3.2.2. Future risk changes of warm/wet and warm/dry events

Based on the analysis above, the future risk of warm and wet events increases, while the risk of dry event decrease in most parts of China. The increasing risk for warm events is more notable than the decreasing risk for wet events. The future risk of compound extremes is conducted in this section. As shown in Fig. 4, the relationship between temperature and precipitation in model simulation is examined firstly. Consistent with the observation, the negative relation between temperature and precipitation is found in model simulation of historical period (1986–2005) and future warming climate. That is, there is a significant negative correlation between temperature and precipitation in most regions of China and this relationship keep constant with global warming.

A statistically significant negative correlation exists between temperature and precipitation in most parts of China in both current climate and the future warming climate. Therefore, in order to analyze the future risk changes of compound extremes, it is necessary to establish the joint distribution of temperature precipitation. According to the method introduced in Section 2.2, the best Copula model, and its parameter, as well as the future PR for a given grid point in three periods (historical period, 1.5 °C and 2 °C warming period) are presented in Table 3. There is a significant negative relationship between temperature and precipitation in the three periods. Meanwhile, the best models are FrankCopula according to the goodness of fit test (P value>0.05), which indicates that the Copula model can describe the joint distribution between summer temperature and precipitation. In addition, the risk of warm/wet event increases by 3.85 times and 6.51 times under 1.5 °C and 2 °C warming, respectively. That is, more frequent of warm/wet events will occur in future warming climate. Furthermore, the best Copula model of the three periods in most other regions passed the

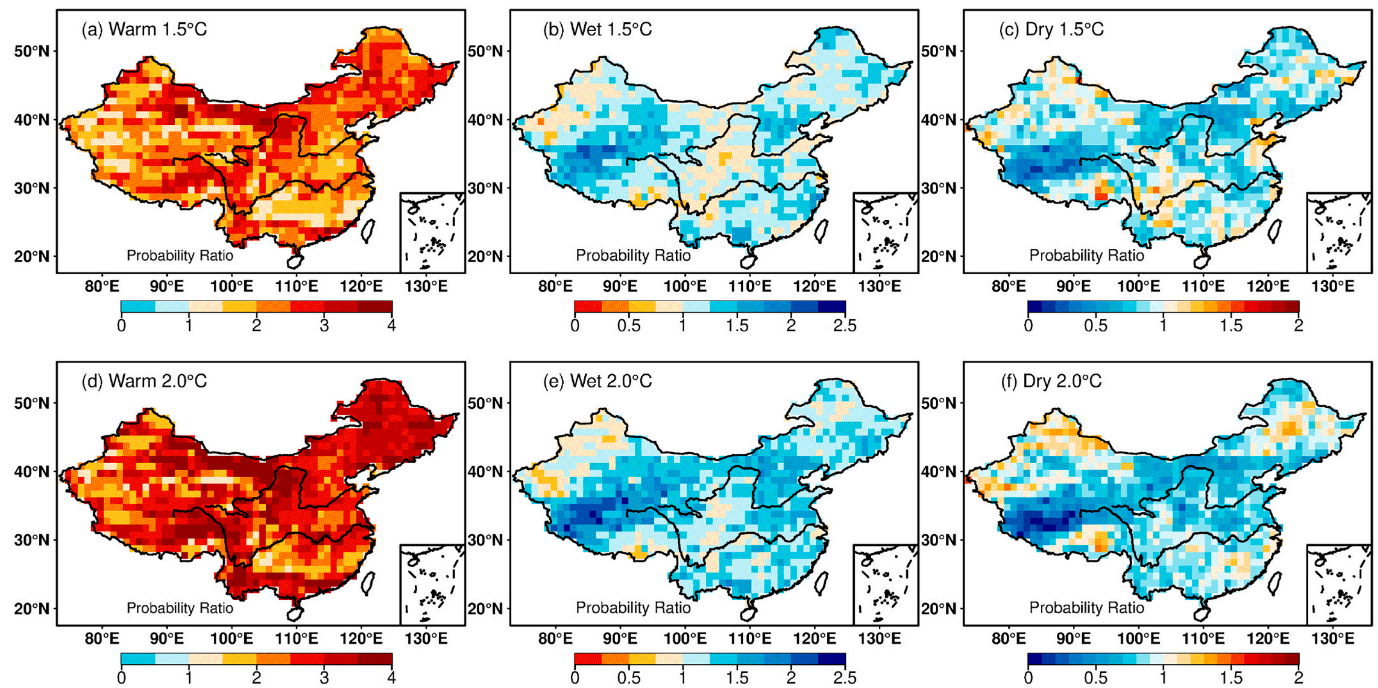

Fig. 3. Spatial distribution of risk of warm events (a, d), wet events (b, e) and dry events (c, f) under 1.5 °C and 2 °C warming relative to historical period.

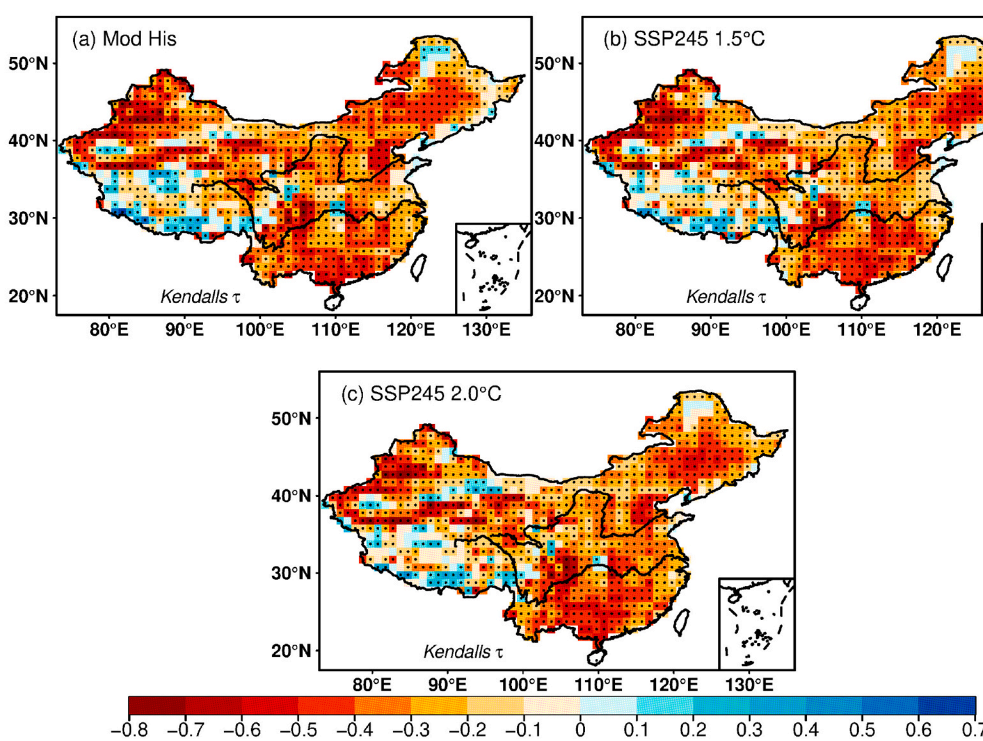

Fig. 4. Spatial pattern of Kendall rank correlation coefficients between temperature and precipitation during historical period (a, 1986–2005) and 1.5 °C (b) and 2.0 °C global warming based on CMIP6 model simulations.

goodness of fit test, except for the Qinghai-Tibet Plateau.

In order to further investigate the future risk changes of compound extremes, Fig. 5 shows the spatial pattern of the risk changes of warm/dry and warm/wet events under different global warming. Compared with the historical period, the regional averaged risks of warm/dry, warm/wet events increase by 1.82, 5.48 times under 1.5 °C warming respectively, and increase by 2.04, 10.01times under 2 °C warming respectively. For 1.5 °C warming climate, the largest increase in risk of warm/dry events are mainly located over eastern Northeast China and central Northwest China, with the risk increasing by 1.5–4 times. The notable changes in the risk of warm/wet events are concentrated over northern North China, eastern Northwest China and South China, with the risk increasing by 7–8 times. The magnitude of changes in risk for warm/wet events are larger than that for warm/dry events. For 2 °C

Table 3
The correlation coefficient between temperature and precipitation, the best Copula model (the bold) and its goodness of fit test *p* values, model parameters, and PR values at given grid point in the historical period (1986–2005) (lon = 118.75°E, lat = 28.75°N), 1.5 °C warming, 2 °C warming. Kendall rank correlation coefficient of the three periods significant at 0.1 level.

Time period	Correlation coefficient	AIC value of different copula models				P value	Model parameters	PR
		Clayton	Gumbel	Frank	Joe			
Historical	−0.26	2.00	2.01	**−15.80**	2.01	0.06	−2.47	–
1.5 °C warming	−0.24	2.01	2.00	**−14.66**	2.01	0.65	−2.30	3.85
2.0 °C warming	−0.26	2.00	2.01	**−17.02**	2.01	0.34	−2.43	6.51

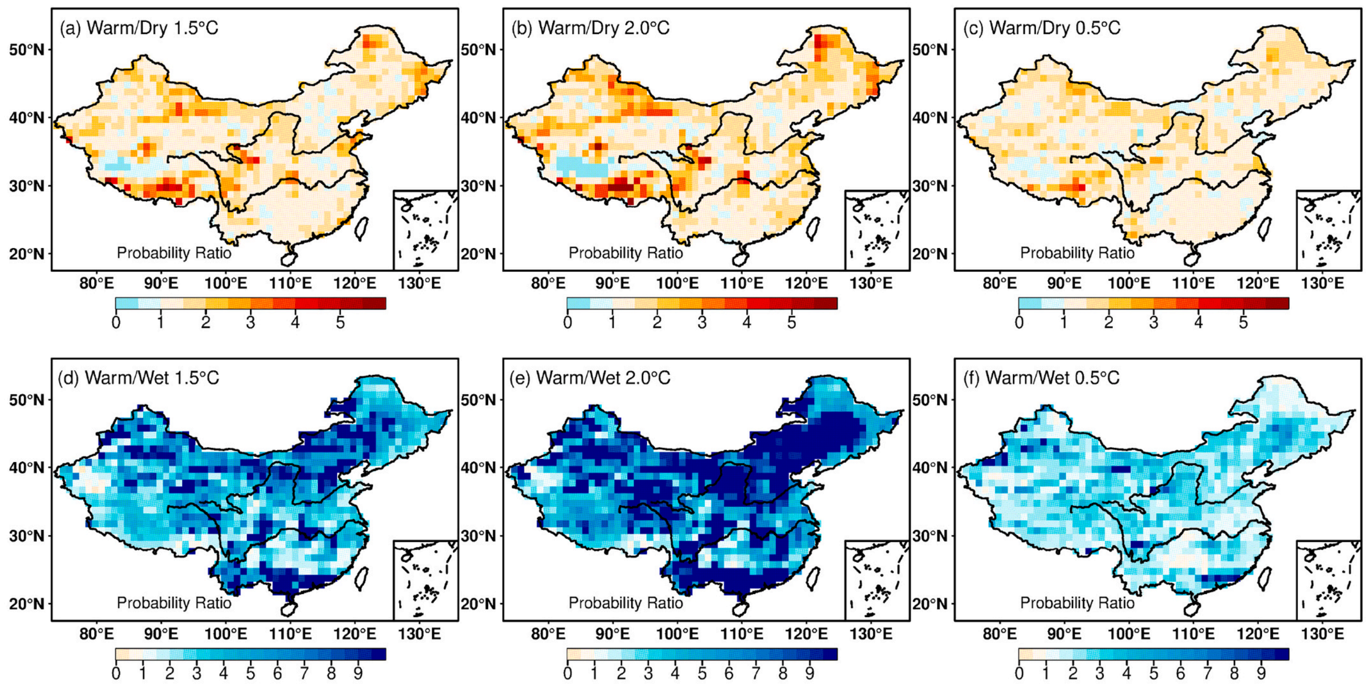

Fig. 5. Risk of warm/dry (a-b) and warm/wet (d-e) events under 1.5 °C and 2.0 °C warming. The risk of warm/dry (c) and warm/wet (f) events under additional 0.5 °C warming from 1.5 °C to 2 °C.

warming climate, the pattern of risk change of the warm/dry event is basically the same as that in 1.5 °C warming climate. The areas with significant increase in risk of warm/wet event have further expanded to western Northeast China, North China, Northwest China, and southern South China, with the risk increasing by more than 8 times. In addition, an additional 0.5 °C warming from 1.5 °C to 2 °C make the risk of regional averaged warm/dry and warm/wet events increased by 1.40 and 2.74 times, respectively. The risk of warm/dry and warm/wet events increases in most parts of China. This indicates that the risk of warm/wet and warm/dry events increases significantly in most regions of China under different warming climate with larger increase magnitude of warm/wet than warm/dry event, and that limiting warming to 1.5 °C rather than 2 °C will help avoid more occurrence of warm/wet and warm/dry event.

4. Conclusions

The observed probability of univariate events and compound extremes during current climate are investigated by using observation dataset with high resolution. The univariate events in this study includes warm, wet, and dry events, and the compound extremes include warm/dry and warm/wet events, all defined by using copula families. The future changes in risk of univariate events and compound extremes under 1.5 °C and 2 °C warming are further investigated using CMIP6 models. The results showed that:

(1) The recurrence period of compound event is longer than its corresponding univariate events in current climate, indicating that the potential impact caused by compound events may be underestimated in the event of the univariate events considered. The statistically significant negative relationship between temperature and precipitation observed in most parts of China can well be simulated by CMIP6 models, which improve our confidence in our results.
(2) The regional averaged risk of warm and wet events will increase by 2.30 and 1.16 times under 1.5 °C warming respectively and increase by 2.83 and 1.29 times under 2 °C warming respectively. The risk increases obviously in Northeast and Northwest China while the risk of dry events decreases in most parts of China.
(3) The future risk changes for warm/wet events show larger increase than that for warm/dry events. The regional averaged risk of warm/dry and warm/wet events will increase by 1.82 and 5.48 times under 1.5 °C warming respectively, while increase by 2.04 and 10.01 times under 2 °C warming respectively. Under 1.5 °C warming, the risk of warm/dry events increase over eastern Northeastern China and central Northwest China, with the risk increasing by 1.5–4 times. Regions over northern North China, eastern Northwest China and South China will experience the highest increase in the risk of warm/wet events with increasing by 7–8 times. For 2 °C warming climate, the areas with the largest increase in risk of warm/wet events have further expanded to

most parts over Northern China and South China, with the risk increasing by more than 8 times.

It should be noted that the coupling relationship between temperature and precipitation has been increasing during paste decades, which resulted that the significant increasing of summer warm/wet and warm/dry events over China (Wu et al., 2019). In addition, the risk of those events in most parts of East Asia will continue to increase under global warming (Zscheischler et al., 2017; Vogel et al., 2020). The definition of compound events in some of those researches are based on emiprical method, the findings about the futher projection of compound events are in agreement with our results.

In this study, we only discussed risk changes of compound extremes temperature and precipitation events over 75% quantiles based on 6 climate models under warming 1.5 °C and 2 °C. The future risk of extreme compound events with long return period needs to be investigated, because changes of such events would lead to large socioeconomic losses (Li et al., 2021). The physical mechanism behind the occurrence of compound event should be further analyzed, which can not only shed light on the evolving of compound in the warming world, but also improve the reliability of the future projection. GCMs exhibit a poor performance in simulating the climate change over regional scale due to the coarse resolution and lack of the physical progress. Thus, dynamical downscaling techniques considering key physical processes determining compound events are expected to provide more accurate future projection at the regional scale.

The attribution of the compound events is the hot topic in the climate researches. The quantification of different external forcing on the changes in the compound events not only can improve the reliability of projection but also can deepen our understanding the human influence on the compound events (Seo et al., 2021). The projection of compound events based on the results from the attribution will be our next work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge the World Climate Research Programme' s Working Group on Coupled Modeling and the modeling groups for making their simulations available for analysis and the Program for Climate Model Diagnosis and Interpretation for collecting and archiving the CMIP6 model output (http://esgf.llnl.gov.). This work was supported by the National Key Research and Development Program of China (Grant No. 2017YFA0603804 and 2018YFC1507704).

References

AghaKouchak, A., Cheng, L., Mazdiyasni, O., Farahmand, A., 2014. Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. Geophys. Res. Lett. 41, 8847–8852.
AghaKouchak, A., Chiang, F., Huning, L.S., Love, C.A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S.M., Ragno, E., Sadegh, M., 2020. Climate Extremes and compound Hazards in a Warming World. Annual Review of Earth & Planetary Sciences. 48, 519–548.
De Luca, P., Messori, G., Faranda, D., Ward, P.J., Coumou, D., 2020. Compound warm–dry and cold–wet events over the Mediterranean. Earth Syst. Dynam. 11, 793–805.
Dong, S., Sun, Y., Aguilar, E., Zhang, X., Peterson, T.C., Song, L., Zhang, Y., 2018. Observed changes in temperature extremes over Asia and their attribution. Clim. Dynam. 51, 339–353.
Hao, Z., Aghakouchak, A., Phillips, T.J., 2013. Changes in concurrent monthly precipitation and temperature extremes. Environ. Res. Lett. 8, 1402–1416.
Hao, Z., Hao, F., Singh, V.P., 2018a. A multivariate approach for statistical assessments of compound extremes. J. Hydrol. 565, 87–94.
Hao, Z., Singh, V.P., Hao, F., 2018b. Compound Extremes in Hydroclimatology: a Review. Water-Sui. 10, 718.
He, B., Zhai, P., 2018. Changes in persistent and non-persistent extreme precipitation in China from 1961 to 2016. Adv. Clim. Chang. Res. 9, 177–184.
Kojadinovic, I., Yan, J., 2010. Comparison of three semiparametric methods for estimating dependence parameters in copula models. Insurance: Mathematics and Economics. 47, 52–63.
Li, W., Jiang, Z., Zhang, X., Li, L., 2018a. On the Emergence of Anthropogenic Signal in Extreme Precipitation Change over China. Geophys. Res. Lett. 45, 9179–9185.
Li, W., Jiang, Z., Zhang, X., Li, L., Sun, Y., 2018b. Additional risk in extreme precipitation in China from 1.5°C to 2.0°C global warming levels. Chin. Sci. Bull. 63, 228–234.
Li, D., Zou, L., Zhou, T., 2018c. Extreme climate event changes in China in the 1.5 and 2 °C Warmer Climates: results from statistical and dynamical downscaling. Journal of Geophysical Research: Atmospheres. 123, 10215–10230.
Li, M., Jiang, Z., Zhou, P., 2020. Projection and possible causes of summer precipitation in eastern China using self-organizing map. Clim. Dynam. 54, 2815–2830.
Li, W., Pan, R., Jiang, Z., Chen, Y., et al., 2021. Future changes in the frequency of extreme droughts over China based on two large ensemble simulations. Journal of Climate 34, 6023–6035.
Orth, R., Zscheischler, J., Seneviratne, S.I., 2016. Record dry summer in 2015 challenges precipitation projections in Central Europe. Sci. Rep.-UK. 6.
Qian, X., Miao, Q., Zhai, P., Chen, Y., 2014. Cold-wet spells in mainland China during 1951-2011. Nat. Hazards 74, 931–946.
Qian, C., Zhang, X., Li, Z., 2019. Linear trends in temperature extremes in China, with an emphasis on non-Gaussian and serially dependent characteristics. Clim. Dynam. 53, 533–550.
Salvadori, G., De Michele, C., Durante, F., 2011. On the return period and design in a multivariate framework. Hydrol. Earth Syst. Sc. 15, 3293–3305.
Salvadori, G., Durante, F., De Michele, C., 2013. Multivariate return period calculation via survival functions. Water Resour. Res. 49, 2308–2311.
Seo, Y.W., Ha, K.J., Park, T.W., 2021. Feedback attribution to dry heatwaves over East Asia. Environ. Res. Lett. 16, 064003.
Shi, C., Jiang, Z., Chen, W., Li, L., 2018. Changes in temperature extremes over China under 1.5°C and 2°C global warming targets. Adv. Clim. Chang. Res. 9, 120–129.
Shi, C., Jiang, Z., Zhu, L., Zhang, X., Yao, Y., Li, L., 2020. Risks of temperature extremes over China under 1.5°C and 2°C global warming. Adv. Clim. Chang. Res. 11, 172–184.
Sun, C., Jiang, Z., Li, W., Hou, Q., Li, L., 2019. Changes in extreme temperature over China when global warming stabilized at 1.5°C and 2.0°C. Sci. Rep.-UK 9, 1–11.
Vogel, M.M., Hauser, M., Seneviratne, S.I., 2020. Projected changes in hot, dry and wet extreme events' clusters in CMIP6 multi-model ensemble. Environ. Res. Lett. 15, 94021.
Wu, J., Gao, X., 2013. A gridded daily observation dataset over China region and comparison with the other datasets. Chin. J. Geophys. 56, 1102–1111 (in Chinese).
Wu, X., Hao, Z., Hao, F., Zhang, X., 2019. Variations of compound precipitation and temperature extremes in China during 1961–2014. Sci. Total Environ. 663, 731–737.
Wu, J., Han, Z., Xu, Y., Zhou, B., Gao, X., 2020. Changes in Extreme Climate Events in China Under 1.5°C–4°C Global Warming Targets: Projections Using an Ensemble of Regional Climate Model Simulations. Journal of Geophysical Research: Atmospheres 125 (e2019JD031057).
Zhai, P., Pan, X., 2003. Trends in temperature extremes during 1951–1999 in China. Geophys. Res. Lett. 30, 1913.
Zhai, P., Zhang, X., Wan, H., Pan, X., 2005. Trends in Total Precipitation and Frequency of Daily Precipitation Extremes over China. J. Clim. 18, 1096–1108.
Zhu, H., Jiang, Z., Li, J., Li, W., Sun, C., Li, L., 2020. Does CMIP6 Inspire more confidence in Simulating climate Extremes over China? Adv. Atmos. Sci. 37, 1119–1132.
Zscheischler, J., Orth, R., Seneviratne, S.I., 2017. Bivariate return periods of temperature and precipitation explain a large fraction of European crop yields. Biogeosci. Discuss. 14, 3309–3320.