Evolution of future precipitation extremes: Viewpoint of climate change classification

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Abstract
Climate change is often described as the average changes in temperature and precipitation; however, it is the change in climate extremes determines the levels of socio-economic impacts related to climate change. It is generally believed that global warming drives increase in frequency, intensity and duration of precipitation extremes, but these changes vary regionally. Focusing on the relationships between evolution of extreme events and long-term climate change, here we propose a novel classification scheme based on Köppen’s system and changes in mean and variability of precipitation, divide the global climate into 20 different changing types and reveal the regional evolution of precipitation extremes. We find that precipitation extremes ascend significantly in wetting regions, especially in tropical and temperate zones, independent with changed variability. As for drying regions, the evolution of extremes is related to precipitation variability. An increase of extremes can still be detected in fluctuant-drying areas, while a slight decrease can be seen in stabilized-drying areas. It is surprising to find increase in both wetness and dryness extremes which implies higher intensity of meteorological hazards in densely populated areas. Based on the current and projected growth of population exposure to precipitation extremes, we identify some hotspots with high potential risk in the future.

KEYWORDS
climate change, climate classification, precipitation extremes, future scenario, population exposure
### 1 | INTRODUCTION

How to mitigate impacts of climate changes is a challenging task. In 2015, nearly 200 parties signed the Paris Agreement on the basis of the United Nations Framework Convention on Climate Change (UNFCCC), urging the most widespread international collaboration in holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. Global warming is believed to boost the frequency, intensity and duration of extreme events (Easterling et al., 2000; Allan and Soden, 2008; Diffenbaugh et al., 2017), therewith amplify meteorological hazards and hence promote disaster risks in the future, endanger the sustainable development of human society (James et al., 2014; Hansen and Cramer, 2015; Carleton and Hsiang, 2016; AghaKouchak et al., 2020; Liu et al., 2020). Precipitation changes are more localized than temperature at regional and global scales, thus precipitation extremes show high regional complexity and spatiotemporal variation (Coumou and Rahmstorf, 2012; Toreti et al., 2013; Xu et al., 2019).

Global terrestrial distribution of historical observation data indicates the disequilibrium of sizes between the areas with increased precipitation extremes and decreased extremes, the former is much larger (Alexander et al., 2005; Groisman et al., 2005; Donat et al., 2013; Fischer and Knutti, 2014). Specifically, some areas dominated by decreased total precipitation still show an increase in extreme events (Kharin et al., 2013; Westra et al., 2013). The interannual variability of precipitation is also related to the frequency, intensity and duration of precipitation extremes on regional scales (Grimm, 2011; Berg and Hall, 2015). The IPCC point out that the changes in mean, variance, or shape of probability distributions of climatic variables can result in unprecedented extreme events (IPCC, 2012). Simulations by ensemble climate models suggest that, with exception of arid region in subtropics, the intensity of precipitation extremes will generally continue to increase, even in the areas with declining total precipitation (Kao and Ganguly, 2011; Kharin et al., 2013).

Due to spatial differentiation of the global climatic conditions, a rational and refined classification method is critical for analysis the evolution of extreme events. Climate state can be regarded as the starting point of regional climate change, as well as extreme events, and can also determine their impacts to a certain extent. In the study of Kittel et al. (1998), seven subcontinental areas are selected as the study regions based on population and food production to evaluate applicability of climate models. Giorgi and Francisco (2000) further divide the globe into 21 regions based on climatic and physiographic factors subjectively, and analyse the spatial pattern of extreme events. The Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation issued by IPCC divides the globe into 26 regions and quantitatively estimates the changes in return periods of temperature and precipitation extremes (IPCC, 2012). In summary, each of these division methods hinge on physical geography, climatology or socioeconomic factors but not specific indicators, bring vagueness of regional variation in climate states and climate changes.

In terms of climate classifications, a bunch of researches have appeared (Feddema, 2005; Kottek et al., 2006; Peel et al., 2007; Strahler and Strahler, 2013). The impacts of climate change on climate classifications have been analysed by many studies (Rubel and Kottek, 2010; Chen and Chen, 2013). Wherein, Köppen system develops the series of detailed indicators related to temperature and precipitation to classify the world into different climate types. The classifications given by Köppen system are consistent with the actual vegetation and soil characteristics, and have been widely applied worldwide (Rubel and Kottek, 2010; Larson and Lohrengel, 2011; Mahlstein et al., 2013; Rohli et al., 2015; Beck et al., 2018).

Inspired by these previous achievements, here we propose a novel classification scheme on the basis of Köppen system, and overlay the changes in the mean and variability of precipitation, in order to reveal climate state and climate change simultaneously on a global map. In the study, the ensemble simulation of climate models in Coupled Model Intercomparison Project 5 (CMIP5) are applied to classify the global land into 20 different types of climate change during the period of 2021–2080 under RCP 4.5 moderate emission scenario. Moreover, a set of precipitation extremes indices are selected to verify the rationality and availability of this novel classification, by which the evolution of precipitation extremes is revealed. The scientific issues are addressed in this study as follows: (a) How to identify the regional differences of global climate change? (b) What is the relationship between the evolution of precipitation extremes and long-term climate change? (c) Where will be the potential high-risk areas of precipitation extremes in the future?

### 2 | MATERIALS AND METHODS

#### 2.1 | Data resource

We analyse the simulations from 20 models in the CMIP5 project (Table S1 in the Supporting Information), which are selected based on the availability of daily temperature
and precipitation for RCP4.5 scenario (i.e., moderate carbon emission) for the period of 2021–2080 (Taylor et al., 2012). The multimodel ensemble mean (MME) in CMIP5 project effectively reduces the uncertainty of the simulations, and well presents the observed patterns of temperature, precipitation and its related extremes, which has been verified in numerous researches (Kharin et al., 2013; Sillmann et al., 2013; Scoccimarro et al., 2016). Only the first ensemble member (“r1i1p1”) of each model simulation is adopted. To facilitate the intercomparison of different models, we reformat all outputs to a common 0.5° × 0.5° resolution by bi-linearly interpolation, and only the values over global land (Antarctica is excluded) are involved.

2.2 Köppen classification method

The Köppen system has remained as the preferred climatic classification because of its explicit indices and usability. The indices are settled by the inherent overlap of climatic types, landforms, biomes and soil orders. Global monthly temperature and precipitation datasets are developed based on MME method. The criterions of Köppen classifications are shown in Table 1, among which the calculation method of arid climate can be referred to Beck’s work (Beck et al., 2018). The global land is divided into five climate zones based on the Köppen system, including tropical, arid, temperate, cold and polar zones (Figure 1).

2.3 Precipitation extremes indices

The Expert Team on Climate Change Detection and Indi-
ces (ETCCDI) has defined a set of indices to facilitate analysis of the characteristics of climate extremes. Base

on the frequency, intensity and duration of extreme
events, we adopt very heavy precipitation days (R20mm),
maximum five-day precipitation (RX5day), precipitation
due to very wet days (R95pTOT), consecutive wet
days (CWD), consecutive dry days (CDD), totally five indices to picture the evolution of precipitation extremes:

1. R20mm: count of days with daily precipitation amount ≥20 mm.
2. RX5day: largest precipitation amount during consecutive 5-day period.
3. R95pTOT: precipitation due to very wet days (>95th percentile of precipitation on wet days in the base period 1961–1990)
4. CWD: maximum length of wet spell (daily precipitation amount ≥1 mm)
5. CDD: maximum length of dry spell (daily precipitation amount <1 mm)

2.4 Calculation of population exposure

The population exposure is defined as the product of the regional climate extreme days and the population (Jones et al., 2015). In the research, we adopt population exposure in each climate zone to provide a qualitative assessment of potential risk in future scenario. The annual R20mm is selected as the criterion of extreme precipitation days, and superimposed with projected population in the calculation. The population data set is available at Socioeconomic Data and Applications Center (SEDAC), with decadal intervals for 2000–2100 and a resolution of 1 km on global land (Gao, 2020). The moderate scenario in Shared Socioeconomic Pathways (SSP2) is selected to simulate the changes in population exposure, which is corresponded with RCP4.5 moderate emission pathway (O’Neill et al., 2017).

TABLE 1 The criterion of Köppen climate classifications

| Classification      | Criterion       |
|---------------------|-----------------|
| A Tropical climate  | Tmin ≥ 18°C     |
| B Arid climate      | Pann < 10 Pth   |
| C Temperate climate | −3°C < Tmin < 18°C |
| D Cold climate      | Tmin ≤ −3°C     |
| E Polar climate     | Tmax < 10°C     |

Notes: Tmax = the air temperature of the warmest month (°C). Tmin = the air temperature of the coldest month (°C). Pann = mean annual precipitation (mm/a). Pth = 2 × Pann if >70% of precipitation falls in winter. Pth = 2 × Pann + 28 if >70% of precipitation falls in summer, otherwise Pth = 2 × Pann + 14. Summer (winter) is the six-month period that is warmer (colder) between April–September and October–March.
3 | GLOBAL CLASSIFICATIONS OF CLIMATE CHANGE

3.1 | Changes in mean and variability of precipitation

MME analysis of the annual precipitation differences indicates that annual precipitation increases among 71.5% of global land (Figure 2a) between latter half period (2051–2080) and former half period (2021–2050), including North and East Europe, most of Asia (except West Asia), central Africa, northern and eastern North America, Wherein, annual precipitation in East Asia, Southeast Asia and eastern North America uplifts over 20 mm. On the other hand, a decrease in annual precipitation occurs in nearly 30% of global land, which mainly distributes in the Mediterranean, West Asia, southern Africa, Australia, southern North America and most of South America.

Based on the difference between later half and former half period, the interannual variability is projected to enhance over 67.7% of global land (Figure 2b), including central Africa, North Asia, East Asia, Southeast Asia, western Australia, eastern United States, Amazon Plain. Especially in southern China, Indochina Peninsula, northern and eastern Malaysia, Amazon Plain, the variabilities uplift over 10 mm. On the other hand, attenuate variabilities appear on west Europe, Mediterranean, Sahara, southern Africa, Iranian plateau, eastern India, Yangtze basin, southern Malaysia, central and eastern Australia, Southwest coast of North America, west and northeast coast of South America.

3.2 | Classifications of climate change

A three-level classification system of climate change is proposed based on the Köppen system and the changes in the mean and variability of annual precipitation. In the first level, the Köppen system is applied to classify the globe into five climate zones, namely tropical (A), arid (B), temperate (C), cold (D) and polar (E) zone. In the second level, the changing trends of annual precipitation are adopted to classify each climate zone into wetting (W) or drying (D) region. In the third level, the changes in precipitation variability are adopted to subdivide each region into fluctuant (f) or stabilized (s) climate type, according to the enhancing or declining of interannual precipitation fluctuations. Here, we present 20 different types of climate change given by the classification described above, assembled by climate zones-precipitation trends-status of precipitation fluctuations in sequence. For instance, tropical-wetting-fluctuant (AWf), tropical-wetting-stabilized (AWs), tropical-drying-fluctuant (ADf) and tropical-drying-stabilized (ADs). The entire classification can be seen in Table S2 in the supporting information. Global classifications of climate change are mapped by ArcGIS software, shown in Figure 3.

In tropical zone, the tropical-wetting type (AW) accounts for 9.5% of global land, distributing in equatorial Africa, southern India, coastal Bengal Bay, Southeast Asia and northeastern Brazil. The tropical-drying type (AD) accounts for 7.8%, scattering among Central Africa, Zambia, Madagascar, southern Indonesia, northern Australia, Central America and northern South America.

In arid zone, the arid-wetting type (BW) accounts for 9.3% of global land, distributing in Sudan grassland, Somali peninsula, southern Arabian peninsula, Indian desert, Caspian lowland, Kazak hills, Mongolian plateau, Victoria desert and central Argentina. The arid-drying type (BD) accounts for 14.6%, covering Sahara desert, south of the Mediterranean, Kgalagadi desert, northern Arabian peninsula, Iranian Plateau, Turan Plain, Australia and Colorado Plateau.

FIGURE 2 | Spatial differences in (a) annual precipitation and (b) interannual variability of precipitation between latter half period (2051–2080) and former half period (2021–2050) [Colour figure can be viewed at wileyonlinelibrary.com]
In temperate zone, the temperate-wetting type (CW) accounts for 7.2% of global land, including central Europe, southern China, Ganges plain, south Korea, Honshu island, New Zealand, southern United States and Parana Plateau. The temperate-drying type (CD) presents 5.4% of global land, scattering among western Europe, north of the Mediterranean, Zimbabwe, South Africa, southeast coast of Australia, Mexican plateau, western Bolivia, northwestern Argentina and Patagonia plateau.

Cold climate zone covers 37.8% of global land, in which the cold-wetting type (DW) accounts for the vast majority, including eastern Europe, Russia, northern China, Alaska, Canada and northern United States. It also indicates that increased precipitation is the main feature of future climate in cold zone. The cold-drying type (DD) only presents 0.9% and locates in central part of North America.

Polar zone mainly distributes in Greenland, Arctic Archipelago, Tibet Plateau and Antarctica. Since there are no observations to verify model simulations, the Antarctic is excluded in the study. The rest of polar zone, covering 8.7% of global land, all belongs to wetting type (EW), which is similar to the changing characteristics of cold zone.

4 | EVOLUTION OF PRECIPITATION EXTREMES

4.1 | Spatial variation

According to the extreme climatic indices defined by Expert Team on Climate Change Detection and Indices (ETCCDI), we adopt five precipitation extreme indices, R20mm, RX5day, R95pTOT, CWD and CDD to illustrate the spatiotemporal changes in precipitation extremes. Projections given by ensemble simulations indicate that precipitation extremes are mainly distributed in South Asia, East Asia, Southeast Asia, northern South America, northern Australia and southern Africa. Comparing the spatial differences of precipitation extremes of later period (2051–2080) to former period (2021–2050), we find R20mm increases in 85.4% of global land, among which >1 day anomaly of R20mm appears in southeast Asia,
southern China, Japan, northeastern United States, west coast of Canada and Peru (Figure 4a). The differences of RX5day and R95pTOT share a similar spatial pattern, and the areas of increased extremes account for 88.5 and 90.6% of global land, respectively. An over 4 mm anomaly of RX5day and >20 mm R95pTOT is projected in southeast Asia, southern and eastern China, southern India, Bangladesh, Nepal, the eastern and northwestern coasts of North America, Colombia, Ecuador, Peru and parts of Brazil (Figure 4b,c). CWD shares a different changing trend with other indices. In South America, equatorial Africa and southern Indonesia, CWD goes down while R20mm goes up, which further indicates the amplification of extremeness (Figure 4d). Areas with increased CWD account for 57.9% of global land, distributing in northeastern India, Nepal, Indochina peninsula, Malay peninsula, Somalia peninsula and Madagascar. For extreme dryness, an increase of CDD is detected in Mediterranean coast, Sahara, west Asia, southern Africa, Indonesia, Australia, central America and most part of South America, accounting for 46.5% of global land (Figure 4e).

4.2 | Zonal evolution of precipitation extremes

Based on climate change classifications, the zonal differences of extreme indices between latter half period (2051–2080) and former half period (2021–2050) are plotted in Figure 5, revealing the relationship between evolution of extreme events and long-term climate change. R20mm is a key indicator that points to the frequency of precipitation extremes. It uplifts rapidly in wetting regions on global land, especially in tropical and temperate zones with an increment of over 0.5 day, and there is no significant difference between fluctuant and stabilized climate type (Figure 5a). In drying regions, the incremental R20mm is

![Figure 4](https://wileyonlinelibrary.com)
much smaller and differentiated with changed variability. R20mm increases in fluctuant-drying areas, whereas remains constant or goes down in stabilized-drying areas.

The zonal differences of RX5day and R95pTOT represent the changing intensity of precipitation extremes. In the wetting regions of tropical, temperate and cold zones, RX5day and R95pTOT rise by more than 3 and 20 mm, respectively (Figure 5b and c). In drying regions, RX5day and R95pTOT also go up, and the increment in fluctuant-drying areas is higher than that in stabilized-drying areas. As for stabilized-drying areas in arid zone (BDs), the changes in RX5day and R95pTOT are too small to be detected.

The differences in CWD are relatively smaller than that of CDD (Figure 5d,e). For wetting regions, CWD increases in temperate, cold and polar zones, but declines in tropical zones. CWD in drying regions of all the climate zones decreases, especially in tropical zone. CDD increases significantly in the drying regions of all climate zones, with an increment of over 3 days in tropical and arid zones. For wetting regions, CDD increases in tropical and temperate zones, while decreases in cold and polar zones.

4.3 | Potential population risks

A superposition of precipitation extremes and total population in each climate zone is adopted to present a qualitative assessment of potential population risk under moderate future scenario (i.e., RCP4.5-SSP2).
short-term (2021–2050 and long-term (2051–2080) future, the annual R20mm, regional population and population exposure are applied to estimate the potential risks (Figure 6).

The population exposure in tropical and temperate zones is significantly higher than other climate zones. The annual extreme rainfall days of tropical zone are projected to rise to 15 days in the short-term future, along with a population of 2.7 billion persons, resulting in a total exposure of 40.9 (±3.0) billion person-days. AWf and AWs are the two most populous areas in tropical zone, the population of these two areas accounting for 17.5% and 11.6% of the current global population, with growth rates of 12.2 and 11.4% per decade, respectively. Combined with the increased precipitation extremes, the exposure in AWf and AWs in 2051–2080 period will reach 25.3 (±1.7) and 18.8 (±1.3) billion person-days, respectively. The increments of exposure in AWf and AWs are 5.5 (±0.3) and 3.7 (±0.4) billion person-days, ahead of other climate types. These facts indicate that the potential population risk in tropical-wetting regions will increase dramatically in the future.

Temperate zone currently has the largest population among climate zones, accounting for 34.7% of the global population. Under the influence of both decelerate population growth and the large stock of population exposure, the risk level of temperate zone remains high. The fluctuant-wetting areas (CWf) have a population of 1.5 billion, ahead of other climate types. The precipitation extremes in CWf are estimated to increase by 0.5 (±0.1) days compared with that in 2021–2050 period, resulting in an uplifted exposure of 17.6 (±1.2) billion person-days in 2051–2080 period. The exposure of CWs areas are also projected to rise to 7.4 (±0.5) billion person-days in 2051–2080, ahead of most climate types.

To summarize, the wetting regions in tropical and temperate zone (i.e., AWf, AWs, CWf, CWs) have the highest population exposure to precipitation extremes over the globe, and the exposure of tropical zone will elevate further in the future. Therefore, these areas are projected to face the highest potential risk caused by precipitation extremes.

In addition, the increment of population exposure in ADf, Ads, BDs and CDs areas is also relatively larger than others, reaching 0.6 (±0.3), 0.3 (±0.2), 0.3 (±0.1) and 0.2 (±0.1) billion person-days, respectively. Since the frequency of extreme events remains constant in these areas, the changes in exposure are mainly contributed by population growth. The population in arid and cold zones is relatively small, and the frequency of precipitation extremes is also less than that of temperate and tropical

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**Figure 6** Population exposure to precipitation extremes for the period 2021–2050 and 2051–2080 in climate change classifications. (a) precipitation extremes, (b) population, (c) population exposure to precipitation extremes. In each region, left bar presents the period of 2021–2050, right bar presents the period of 2051–2080. The error bars represent the standard errors between simulations [Colour figure can be viewed at wileyonlinelibrary.com]
zones. However, northern China and northeastern United States in cold zone are two populous areas that face certain threat of precipitation extremes. An increment of 0.3 (±0.1) days in precipitation extremes appears on the fluctuant-wetting areas in cold zone (DWF), indicating that the hazard monitoring and early warning capabilities should be further strengthened in the future.

5 | CONCLUSIONS

It is generally believed that the changes in the mean, variance and distribution shape of climatic elements lead to changes in extreme events. However, the global divisions applied in previous studies of climate extremes is not clearly related to climate state or climate change. Thus, how to reveal the relationship between climate extremes and long-term climate change on a regional scale has become a scientific issue. Based on this idea, we develop a novel climate classification method, integrate climate state and climate changes simultaneously on a global map and divide the globe into 20 types. Once the global division has been made, an analysis by zones of the evolution of extreme rainfall events and their influence on the risk for the population is carried out under future scenarios. The results demonstrate the regions with the greatest potential risk from extreme precipitation events in the coming decades.

In tropical-wetting region, both the intensity and frequency of precipitation extremes are projected to increase dramatically in the future. The intensity also enhances at a lower rate in tropical-drying region, while the frequency remains relatively constant. Maximum length of wet spell shortens in most of tropical zone, while the maximum length of dry spell generally elongates, especially in drying regions.

In arid-wetting region, the frequency and duration of precipitation extremes changes in similar ways, but the maximum intensity of precipitation goes up significantly. The conductive dry days in the arid-drying region increase dramatically, suggesting a longer duration of extreme dryness in the future. The changes in extreme rainfall are very limited in drying regions.

In temperate-wetting region, both the frequency and intensity of precipitation extremes go up significantly, and the increment of intensity in fluctuant-wetting areas is higher than that in stabilized-wetting areas. The duration indices barely change in temperate zone. In temperate-drying region, the changes in the intensity and frequency of extremes are relatively small, but the increments of fluctuant-drying areas are still greater than that in stabilized-drying areas.

Cold zone and polar zone are characterized by uplifted precipitation in all areas. The intensity and frequency of precipitation extremes tend to ascend with wetting climate, and the fluctuant and stabilized types differ slightly. The maximum length of dry spell shortens in cold zone and polar zone, while the maximum length of wet spell elongates slightly.

The population exposure to precipitation extremes is analysed on the basis of climate classifications to reveal the potential high-risk regions. The population exposure of AWf, CWf and AWs are the top three in 2021–2050 period, reaches 19.7, 17.7 and 15.2 billion person-days, respectively. Meanwhile, the population exposure of AWf and AWs grow rapidly, with a projected increment of 5.5 and 3.7 billion person-days in the future, ahead of all the rest types. Therefore, AWf, CWf and AWs areas will face the highest potential population risk caused by precipitation extremes. Additionally, the population exposure of CWs, ADf and ADs areas is at moderate level, but their potential risks are comparatively higher than other areas, thus a further improvement of climate risk management is necessary in the future.

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AUTHOR CONTRIBUTIONS

Shao SUN: Data curation; formal analysis; funding acquisition; investigation; methodology; project administration; visualization; writing - original draft; writing-review & editing. Peijun Shi: Conceptualization; formal analysis; methodology; project administration; resources; supervision; visualization; writing-review & editing. Qiang Zhang: Data curation; funding acquisition; writing - original draft; writing-review & editing. Jing’ai Wang: Methodology; resources; visualization; writing-review & editing. Jianguo Wu: Formal analysis; resources; writing-review & editing. Deliang Chen: Formal analysis; methodology; resources; writing-review & editing.

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