Wetness over the China mainland under the 1.5°C global warming in a regional climate model ensemble

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Abstract. The study examines the wetness over the China mainland under the 1.5°C global warming using the 3-monthly Standardized Precipitation Index (SPI) based on an ensemble of CORDEX regional climate models. Results indicate that the Northwest China is characterized by more severe wetness than the other subregions. And the winter shows the largest wetness among the four seasons, especially for North China, Northeast China and Northwest China, with the ensemble mean and median of their regionally averaged SPI showing abnormally wet.

1. Introduction
In 2015, the United Nations Framework Convention on Climate Change approved the Paris Agreement, which deals with greenhouse gas emissions mitigation and adaptation [1]. The agreement aims to keep the increase in global average temperature to below 1.5°C above pre-industrial levels, which would significantly reduce risks and the impacts of climate change. Plenty of studies have been analyzed towards either the globe or some specific areas based on global and regional climate models [2].

The Coordinated Regional Downscaling Experiment (CORDEX) is an international framework under the World Climate Research Programme [3] with a common specification for model domains, contributing to the investigation of the multi-model ensemble for the limited area of interest based on the available regional climate models. It bridges the fundamental gap in the spatial scale of the climate information from the CMIP5 models and that required by the governments. Previous studies have revealed that the precipitation characteristics would change to a great extent under the global warming, which brings about disasters of droughts and floods causing conspicuous impacts on the natural and human systems [4]. China is characterized by varied topography and complex climate features [5], and it could suffer from the climate change over different subregions. Therefore, it makes great sense to investigate the wetness risks over the China mainland under the global warming of 1.5°C.

The paper is structured as follows. Descriptions of the used data and methods are described in Section 2. In Section 3, the projected wetness over the China mainland under the 1.5°C global warming from an ensemble of CORDEX RCMs is presented. Section 4 provides the conclusion and discussion.

2. Data and methods

2.1. The CORDEX model data
The investigations are based on the 6 RCM runs under the CORDEX framework, which are available under the historical base and two representative concentration pathway scenarios (RCP 4.5 and 8.5)
for the East Asia. A brief introduction of the regional climate models (RCMs) and driving global climate models (GCMs) are provided in Table 1. Hereafter, the specific RCM driven by a GCM will be marked as the RCM (GCM), e.g. the CCLM5 (CNRM-CM5) refers to the CCLM5 run driven by CNRM-CM5.

The CORDEX East Asia experiments are carried out with a resolution of 0.44° to the domain shown in Figure 1. The China mainland is divided into 8 subregions based on the societal and geographical conditions in order to better investigate the local climate in different subregions [6].

Table 1. Summary of the climate model projections used in this study.

| GCM       | Institute                        | RCM     | Institute       |
|-----------|-----------------------------------|---------|-----------------|
| CNRM-CM5  | CNRM-CERFACS, France              | CCLM5-0-2| CLM Community   |
| EC-EARTH  | ICHEC, Netherlands/Ireland        | CCLM5-0-2| CLM Community   |
| EC-EARTH  | ICHEC, Netherlands/Ireland        | HIRHAM5 | DMI, Denmark    |
| HadGEM2-AO| MOHC, UK                          | HadGEM3-RA| MOHC, UK       |
| HadGEM2-ES| MOHC, UK                          | CCLM5-0-2| CLM Community   |
| MPI-ESM-LR| MPI-M, Germany                    | CCLM5-0-2| CLM Community   |

Figure 1. The CORDEX East Asia domain and the model orography (shading: units: m), the black boxes represent the 8 subregions of the China mainland: North China (NC, 36°N-46°N, 111°E-119°E), East China (EC, 27°N-36°N, 116°E-122°E), Central China (CC, 27°N-36°N, 106°E-116°E), South China (SC, 20°N-27°N, 106°E-120°E), Northeast China (NE, 39°N-54°N, 119°E-134°E), Northwest China (NW, 36°N-46°N, 75°E-111°E), Southwest China (SW, 22°N-27°N, 98°E-106°E), the Tibetan Plateau (TP, 27°N-36°N, 77°E-106°E).

2.2. Definition of the 1.5°C global warming

The temporal sequences of annual global surface air temperatures from the driving GCMs are first smoothed by a 30-year running method to eliminate the interannual variability [7]. To identify a relatively stable climate mode, the 30-year period with the running mean temperature reaching 1.5°C higher than the pre-industrial (1881–1910) global mean temperature is defined as the global warming (GW) threshold crossing time under the scenarios. The warming consequences are presented as the climate differences between the GWs and the historical reference period of 1956-2005.

2.3. The standardized precipitation index

The Standardized Precipitation Index (SPI) is a statistical indicator recommended to be used by all meteorological and hydrological services worldwide to characterize features of drought and wetness [8]. It compares the precipitation during a period with the long-term rainfall distribution for the same time period. The reference period and the period of 1.5°C GW are merged, and then the wetness condition under GW can be detected by the 3-monthly SPI of GW periods [9, 10]. Table 2 gives a brief introduction to the interpretation of different values of SPI.
Table 2. Drought and wetness categories for the SPI, derived from the NOAA NCDC. Negative and positive SPIs represent drought and wetness, respectively. $A_{SPI}$ refers to the absolute value of SPI.

| Threshold  | Interpretation       | Threshold  | Interpretation       |
|------------|----------------------|------------|----------------------|
| $A_{SPI} \leq 0.5$ | Near normal          | $1.3 < A_{SPI} \leq 1.6$ | Severely dry / wet   |
| $0.5 < A_{SPI} \leq 0.8$ | Abnormally dry / wet | $1.6 < A_{SPI} \leq 2.0$ | Extremely dry / wet  |
| $0.8 < A_{SPI} \leq 1.3$ | Moderately dry / wet | $A_{SPI} > 2.0$ | Exceptionally dry / wet |

2.4. The signal-to-noise ratio

The signal-to-noise ratio (SNR) is used to measure the credibility of the estimated results consulted from an ensemble [11]. It is defined as:

$$SNR = \frac{Signal}{Noise}, \quad Signal = x_e, \quad Noise = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - x_e)^2}$$

The $x_i$ refers to the result of an individual model in an ensemble of $n$ models, while $x_e$ denotes the ensemble result, which is always represented by the ensemble mean or median. The SNR greater than 1.0 indicates that the signal is greater than noise, and the estimated results can be considered reliable.

3. Results

3.1. Wetness over the China mainland under the 1.5°C global warming

Figure 2 shows the spatial distributions of the averaged SPI in spring under the 1.5°C GW over the China mainland derived from the ensembles and individual models. According to the ensemble mean and median, positive SPI dominates most areas of the China mainland. Results indicate the general slight wetness, especially for the NW, where some areas show moderately wet compared with the historical period. The ensemble members have similar performances for the projected wetness distribution, showing increasing SPI and the increasing wetness from the southeast to northwest. The wetness is mainly near normal over the subregions of CC, EC, TP, SW and SC, whereas wet risks characterize the projections over NW, NC and NE but it differs among different ensemble members. Notably, it reaches severely wet risk over some parts of NW under the 1.5°C GW compared to the historical period in the projections of HIRHAM5 (EC-EARTH) and HadGEM3-RA (HadGEM2-AO).

Figure 2. Spatial distributions of the spring averaged SPI over the China mainland under the 1.5°C GW derived from the ensemble mean and median, as well as each individual model, the dotted areas in the ensemble mean and median indicate the SNRs greater than 1.0.
As for summer under the 1.5°C GW (Figure 3), the SPI distributions from the ensemble mean and median are similar to those for spring, with positive values over most area but generally smaller than in spring. The differences in projections of different ensemble members are larger in summer than in spring. The four models of CCLM5 (CNRM-CM5), CCLM5 (EC-EARTH), HIRHAM5 (EC-EARTH) and CCLM5 (MPI-ESM-LR) show their SPI maxima over NW under both the RCP 4.5 and 8.5 scenarios. In the HadGEM3-RA (HadGEM2-AO) projection under the RCP 4.5, the highest SPI mainly occurs in NC and NE, while in the projections of HadGEM3-RA (HadGEM2-AO) under the RCP 8.5 and the CCLM5 (HadGEM2-ES) under both RCPs, the highest values of SPI are located in SC. However, in terms of the ensemble mean and median, the SPI maxima appear in NW in summer with lower values than that in spring, which represents the risk of abnormal wetness over there. Although the other regions are projected to be near normal under the 1.5°C GW on the basis of the ensemble mean and median, according to multiple projections, the wet risk cannot be completely excluded over NC, NE and SC.

**Figure 3.** Same as Figure 2, but for the summer averaged SPI under the 1.5°C GW.

In the autumn under the 1.5°C GW (Figure 4), the ensemble members show obvious wet risks in NW, particularly the projection of severe wetness in the HIRHAM5 (EC-EARTH) model. Most of the other areas are projected to be near normal relative to the reference period. In addition, according to the ensemble mean and median, partial NW also shows abnormally wetness risk under the 1.5°C GW. On the other hand, the distribution patterns and value scales of the SPI in autumn is quite similar to that in summer, which show generally lower SPI values than in spring.

In the winter under the 1.5°C GW (Figure 5), mainly positive SPI characterizes most area over the China mainland according to the ensemble mean and median. It shows largest areas with the SPI greater than 0.5 among the four seasons, which cover not only NW but also some parts of NC and NE, indicating the more significant wetness risks over those regions in winter. The SPI maxima in the projections from individual ensemble members are also mostly located over NW, NC and NE, representing the corresponding possible severely wet risks.
3.2. Wetness over different subregions of the China mainland

In spring, most of the SPI values range from 0 to 0.5 under the 1.5°C GW (Figure 6a), which suggests that the subregions all tend to be wet but mostly near normal relative to the historical reference period of 1956-2005. Importantly, the abnormally wet risk is rather significant over NW, with the regionally averaged ensemble mean and median both larger than 0.5. On the other hand, the SPI values of SC and SW are relatively lower and their mean and median are close to 0, indicating that the wetness might not change compared to the reference period over the two subregions under the 1.5°C GW. The uncertainty of the wetness projection in spring over SC is reflected with the global warming.
In the summer under the 1.5°C GW (Figure 6b), the first and third quartiles as well as the ensemble mean and median for the averaged SPI concentrate in 0–0.5 for all subregions with the highest values in NW, which represents the near normal wetness relative to the reference period, but relatively higher wet risk over NW than other subregions. On the other hand, the averaged SPI maximum reaches 0.5 for SC, NE and NW, indicating their probability of abnormally wet risks.

With respect to the wetness projections for autumn under the 1.5°C GW (Figure 6c), the SPI quartiles show similar distribution but tends to be slightly lower compared with those for summer. All the subregions are projected to be near normal in autumn, and only the maximum SPI values of EC and NW are greater than 0.5. The ensemble mean and median of the averaged SPI for SW are both near 0, which are lower than the other subregions, showing non-significant wet risks over SW.

As for the winter under the 1.5°C GW (Figure 6d), the overall SPI quartiles are evidently higher than the other seasons, especially for NC, NE and NW. The averaged SPI of NC has its maximum up to larger than 0.8 and the ensemble mean greater than 0.5, representing the moderately and abnormally wet risk, respectively. In terms of NE, the maximum and the ensemble mean are both above 0.5, whereas those for NW are also larger than 0.5 as well as the third quartile, which indicate the risk of abnormal wetness in winter under the 1.5°C GW over NE and NW. Over the five subregions of EC, CC, SC, SW and TP, it shows mainly near normal wetness under the 1.5°C GW. The SPI values of SW are the lowest among the 8 subregions, with its ensemble mean and median close to 0 and the first quartile lower than 0, which expresses the lowest wetness risk in winter over the China mainland.

Figure 6. Boxplots of the projected seasonal SPI for the 8 subregions over the China mainland under the 1.5°C GW. The top and bottom whiskers are the maximum and minimum projections, respectively. The top and bottom of the boxes represent the first and third quartiles, while the bands inside the boxes are the ensemble medians. The ensemble means are indicated by solid red dots.

4. Conclusions and discussions
Based on the ensemble of CORDEX regional climate models, the wetness over the China mainland under the 1.5°C global warming is analyzed towards different seasons and different subregions using the 3-monthly SPI. It is generally indicated that the NW is always characterized by more severe wetness than the other subregions under the 1.5°C global warming. And the winter shows largest wetness among the four seasons, especially for NC, NE and NW, with the ensemble mean and median of their regionally averaged SPI showing at least abnormally wet. Results further demonstrate the necessity to restrict the global warming. Additionally, investigations are to be carried out in the future using other ensemble methods to eliminate the systematic biases of multiple models [12, 13]. Moreover, the regional wetness is not only impacted by the global warming, but also influenced by the natural variability of the climate [14, 15], which also needs further explorations.

Acknowledgments
This research acknowledges the financial support of the 2018 Nanjing Vocational College of Information Technology Doctoral Special Fund Project (Grant No. YB20180903).

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