Extreme precipitation over East Asia under 1.5 °C and 2 °C global warming targets: a comparison of stabilized and overshoot projections

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Abstract
Highly populated East Asia is vulnerable to extreme precipitation. Here, we use Community Earth System Model low-warming simulations to examine how extreme precipitation events may change in East Asia under the Paris Agreement global warming targets. The frequency and intensity of extreme precipitation will increase markedly over East Asia in the warmer climates. Limiting end-of-century warming to 1.5 °C, in comparison with 2 °C, will reduce the risks of extreme precipitation frequency and intensity in East Asia by 26%–31%, with the greatest reductions (38%–54%) in Japan. A brief overshoot of the 1.5 °C target would affect Mongolia, the Korean Peninsula and Japan from the aspects of regional average. More than 25% of the increase in the frequency and intensity of extreme precipitation in these regions can be avoided during the end of the 21st century (2081–2100) if there is no temperature overshoot, according to the best estimate. Vertical moisture advection is the main contributor to changes in precipitation-minus-evaporation in East Asia in the warmer climates. The increased low-level specific humidity and cyclonic circulation changes are the dominant thermodynamic and dynamical processes that contribute to the increase of precipitation over South China and Japan. Our work suggests that limiting warming to 1.5 °C without overshoot is beneficial to minimizing the impacts associated with precipitation extremes across East Asia.

1. Introduction

Extreme precipitation can lead to natural disasters and cause great economic losses and even mortality (Kunkel et al 1999, Easterling et al 2000, Dewan 2015, Jahn 2015). The risks associated with some extreme-precipitation-related natural disasters have increased in recent decades (IPCC 2013). East Asia is vulnerable to extreme precipitation (Fujibe et al 2006, Zhang et al 2008, Jung et al 2011, Zhao et al 2013, Ren et al 2015). The summer of 2018 saw great flooding due to extreme precipitation in both Japan and China. During late June to mid-July 2018, successive heavy downpours in southwestern Japan resulted in widespread devastating floods and mudflows, with 225 fatalities across 15 prefectures with a further 13 people missing (Kotsuki et al 2019). Heavy rains during late June to mid-July 2018 in central eastern China also induced ruinous floods, leading to large economic losses (Wang et al 2019). Untangling the future changes in extreme precipitation associated with global warming is of critical importance to our adaptation activities.

Both mean and extreme precipitation will increase over most land regions under future global warming (IPCC 2013). The response of extreme precipitation in the East Asian monsoon region is among the greatest across all global monsoon regions, and increases in the magnitude of extreme precipitation will be greater than those of mean precipitation (Kitoh et al 2013). The Paris Agreement has set a goal of ‘holding global warming to
well below 2 °C and pursuing efforts to limit it to 1.5 °C above preindustrial levels’ (United Nations Framework Convention on Climate Change 2015). Multiple climate models have been used to investigate climate change in 1.5 °C and 2 °C warmer climates (e.g. King et al 2017, Nangombe et al 2018, Zhang et al 2018, Zhou et al 2018). Among them, the CMIP (Coupled Models Intercomparison Project) models and dynamical downscaling with regional models have been widely used to access changes in precipitation extremes in different regions of the world (King et al 2017, Zhang and Villarini 2017, Aerenson et al 2018, Chevuturi et al 2018, Dosio and Fischer 2018, Li et al 2018b, Li et al 2018c, Li et al 2018d, Nikulin et al 2018, Wang et al 2018, Zhou et al 2019). Results from the HAPPI (Half-a-degree Additional warming. Prognosis and Projected Impacts) project (Mitchell et al 2017) have also been used to reveal mean precipitation changes in East Asia (Lee et al 2018). However, CMIP-type climate projection do not necessarily represent stabilized conditions, and HAPPI simulations do not consider air–sea interactions, which is important for climate modeling in East Asia (Wang et al 2005, Song and Zhou 2014). Thus, to address the questions of how East Asian precipitation extremes will change in the stabilized 1.5 °C and 2 °C warmer climates and to what extent extreme precipitation impacts can be reduced under stabilized 1.5 °C warming compared with 2 °C warming level, a stabilized projection from fully ocean–atmosphere coupled model is needed. In addition, whether a temperature overshoot (global warming temporarily exceeding 1.5 °C then declining to stabilize at 1.5 °C) should be allowed, from the perspective of extreme precipitation changes in East Asia, should also be determined.

In this study, the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM) low-warming simulations (Sanderson et al 2017), a set of simulations designed specifically for the assessments of climate impacts under 1.5 °C and 2 °C warmer climates, are applied to assess changes in extreme precipitation in East Asia under stabilized 1.5 °C and 2 °C warming scenarios. CESM large ensemble shows some biases in simulating the extreme precipitation over East Asia. The extreme precipitation is overestimated over fully ocean–atmosphere coupled model is needed. In addition, whether a temperature overshoot (global warming temporarily exceeding 1.5 °C then declining to stabilize at 1.5 °C) should be allowed, from the perspective of extreme precipitation changes in East Asia, should also be determined.

2. Data and methodology

2.1. Model data
The model data used in this study are from the CESM low-warming simulations released by NCAR (Kay et al 2015, Sanderson et al 2017), which are specifically designed to study climate change at 1.5 °C and 2 °C warming levels above preindustrial levels and the climate impacts of global warming. In these simulations, a set of greenhouse gas emission pathways was first designed to incorporate long-term global warming simulations that do not exceed 1.5 °C (1.5 °C NE) and 2 °C (2 °C NE) above preindustrial levels, and a scenario in which global warming briefly exceeds 1.5 °C before returning to 1.5 °C (1.5 °C OS) by 2100. The emission pathways were then applied to ensemble members of the CESM for the simulations from 2006 to 2100. Eleven members were compiled for the 1.5 °C NE and 2 °C NE scenarios, and six members were compiled for the 1.5 °C OS scenario. Only greenhouse gas emission pathways differ among the three low-warming scenarios. Other anthropogenic forcings, including aerosol emissions, land use and ozone, follow the RCP8.5 scenario throughout the 21st century. Note that aerosols have large effects on East Asian precipitation (Menon et al 2002, Qian et al 2003) and monsoon circulation (Song et al 2014). Large aerosol changes are projected throughout the 21st century (Lamarque et al 2011) in this region and these can have large effects (King et al 2018). The overshoot scenario was designed to investigate whether a brief temperature overshoot will lead to significant climate change compared with 1.5 °C NE scenario (Sanderson et al 2017). 1.5 °C NE scenario reaches 1.5 °C above preindustrial levels around 2040, and remains at this temperature until 2100. The 1.5 °C OS scenario reaches a peak temperature of 1.7 °C around 2050 before cooling to 1.5 °C by 2100. The 2 °C NE scenario reaches 2.1 °C in 2090 and remains at this temperature until 2100. The horizontal resolution of the CESM is 1° × 1°.

2.2. Baseline, 1.5 °C and 2 °C warming levels and subregions
A baseline period of 1986–2005 is referred to as the present day. The period from 2081 to 2100 is used to represent the stable equilibrium period for 1.5 °C and 2 °C warming relative to preindustrial levels. For the 1.5 °C OS scenario, mid-century (2046–2065; 1.5 °C OS_M) data and end-century (2081–2100; 1.5 °C OS_E) data were used to investigate the effects of temperature overshoot, which is simulated as a brief overshoot above
1.5 °C and a subsequent return to 1.5 °C. In this study, East Asia is classified into four subregions: China (CN), Mongolia (MG), Japan (JP) and the Korean Peninsula (KP), as in previous work (Li et al 2018d).

2.3. Frequency and intensity of precipitation

2.3.1. Frequency

For each grid point, present-day dry days (days with precipitation less than 1 mm day\(^{-1}\)) and wet days (days with precipitation more than 1 mm day\(^{-1}\)) are first calculated. Then, wet-day precipitation is divided into percentiles in steps of 5 between 5 and 95 for each period. This yields the changes in the intensity of precipitation extremes among the different periods.

2.3.2. Intensity

Unlike frequency, the intensity for each grid point is directly calculated by separating the wet-day precipitation into percentiles in steps of 5 between 5 and 95. Present-day percentiles are then used as thresholds to calculate frequencies for the various precipitation percentiles in the warmer climates.

2.4. Return value and return period

The return period events of annual maximum 1-day precipitation amount (RX1 day) are also investigated as indicators of very heavy precipitation. For each grid point in each period, the 20-year RX1 day series is fitted using a generalized extreme value (GEV) distribution and the maximum-likelihood estimation (MLE) (Hosking 1985). The GEV parameters are spatially smoothed at each grid point by the eight surrounding grid points (Kharin and Zwiers 2005) considering the noise in change patterns in extreme precipitation. The return values are then derived from the inverse function of the fitted GEV distributions (Wilks 2011). The return period events in each time period are calculated to derive the changes in intensity of these types of events. Changes in the frequency of present-day 10-year (RV10) and 20-year (RV20) return period events in the four warmer climates are also investigated.

2.5. Precipitation indices

In addition to the return period events, four widely used precipitation indices are used in this study (see table S1 available online atstacks.iop.org/ERC/1/085002/mmedia for index definitions): the simple daily intensity index (SDII), very wet days (R95p), max 5-day precipitation amount (RX5 day) and max 1-day precipitation amount (RX1 day; Zhang et al 2011).

2.6. Avoided impacts and statistical significance test

The impacts of extreme precipitation events that are avoided in the 1.5 °C warmer climate compared with the 1.5 °C OS_M, 1.5 °C OS_E and 2 °C warmer climates are assessed as follows (Li et al 2018a):

\[
AI = \frac{C2.0 - C1.5}{C2.0} \times 100\%
\]

(1)

where AI is avoided impact and C1.5 and C2.0 are the regional mean changes in the 1.5 °C and 2 °C (or 1.5 °C OS_M and 1.5 °C OS_E) warmer climates, respectively, compared with the present day.

Student’s t-test is used to indicate the 10% significance level for the changes in mean and extreme precipitation.

2.7. Moisture budget analysis

A commonly used moisture budget equation is used to investigate the changes in precipitation over East Asia and the underlying physical mechanism, as follows (Chou and Lan 2012, Chou et al 2013):

\[
P' = E' - \partial_t \langle q \rangle - \langle V_h \Delta q \rangle' - \langle \omega \partial_p q \rangle' + \delta,
\]

(2)

where the P, E and q represent precipitation, evaporation, and specific humidity, respectively. The term \(V_h\) is the horizontal vector wind and \(\omega\) is the vertical velocity. \(\langle \rangle\) represents the column integration from the surface to the tropopause. \(\partial_t\) and \(\partial_p\) denote time and pressure derivative, respectively, and \(\nabla_h\) is the horizontal operator. The vertical advection term can be further divided into a dynamic term \(\langle \omega \partial_p T \rangle\) and a thermodynamic term \(\langle \omega \partial_p q' \rangle\). The \(\langle \rangle'\) denotes the departure from mean states \(\langle \rangle\). The seasonal mean value of \(\partial_t \langle q \rangle\) is much smaller than other terms in equation (2) and can be ignored. Therefore, equation (2) can be transformed into

\[
P' = E' - \langle V_h \Delta q \rangle' - \langle \omega \partial_p T \rangle - \langle \omega \partial_p q' \rangle + \delta.
\]

(3)

Each component on the right side of equations (2) and (3) is calculated using the monthly output of the CESM members. The multimember mean is then calculated.
3. Results

3.1. Changes in precipitation structure

To investigate changes in precipitation structure, we first examined the changes in annual and seasonal mean precipitation intensity (SDII). Compared with the present day, in the 1.5 °C and 2 °C warmer climates, the annual SDII will increase significantly in most parts of East Asia, with large centers located in parts of southwestern and southeastern China and southern Japan (figure 1). Regional mean changes in annual SDII in East Asia are approximately 5.5% and 7.3% in the 1.5 °C and 2 °C warmer climates, respectively. A brief overshoot above 1.5 °C will not lead to significant and spatially consistent changes in SDII across the East Asia in comparison to the 1.5 °C warmer climate, but will have regional effects, in particular along the densely populated Yangtze River valley during the end-21st century (figure 1(c)). The annual mean change is dominated by changes in boreal summer (June to August) (figure S1). Wintertime (December to February) will also witness an increase of SDII with centers located in regions between the Yellow River and Yangtze River (figure S2).

To examine the response of precipitation structure to global warming, we compared the regional mean changes of daily precipitation frequency and intensity in figure 2. Dry days will decrease in most parts of East Asia, with a regional average of about −2.0% in the four warmer climates (figure 2(a)). The frequencies of all precipitation percentiles aggregated for East Asia will increase in the warmer climates, and extreme precipitation...
exhibits a stronger response to global warming than light and moderate precipitation. For precipitation stronger than the 95th percentile of the present day, the frequency will increase by approximately 23% and 29% in the 1.5°C and 2°C warmer climates, respectively. Differences in the changes of the frequency of precipitation stronger than the 95th percentile among the 1.5°C, 1.5°C OS_M and 1.5°C OS_E climates are small compared with the ensemble spread. Among the East Asian subregions, increases in the frequency of precipitation stronger than the 95th percentile are largest in China (figures S3(a)–(d)).

Precipitation intensity will increase markedly (figure 2(b)). The regional mean intensities of all precipitation percentiles will increase with global warming. Changes in the intensity of extreme precipitation are stronger than those of light and moderate precipitation. For precipitation stronger than the 95th percentile, the intensity will increase by approximately 7% and 10% in the 1.5°C and 2°C warmer climates, respectively. Regional averaged differences among the 1.5°C, 1.5°C OS_M and 1.5°C OS_E climates are small. Increases in the intensity of precipitation above the 95th percentile are greater in China and Japan than in the other subregions (figures S3(e)–(h)).

3.2. Changes in extreme precipitation events

3.2.1. Changes in return period event

We used RV10 and RV20 as indicators to quantify changes in the risk of flood disasters. The frequency of present-day RV20 will increase significantly in the 1.5°C warmer climate across nearly the whole of East Asia, with centers located in the Tibetan Plateau, southeastern China and the southern Korean Peninsula (figure 3(a)). In comparison with the changes under 1.5°C warming, the present-day RV20 will happen more frequently in regions along the Yangtze River under the 2°C warming target, as evidenced by frequency increases of about 130% for the 1.5°C and 180% for the 2.0°C warming targets relative to the present day.
Compared with the 1.5 °C stabilized warming, the effects of the temperature overshoot are not uniform and are not statistically significant at the 10% significance level in most parts of East Asia in both the mid- and end-century periods (figures 3(b)–(c)). However, an temperature overshoot can cause more extreme precipitation events in some areas, such as parts of southeastern China, southern Japan, the Korean Peninsula and western Mongolia.

We extended the analysis from frequency to intensity and find an enhancement of RV20 (figure 3(e)). Hotspots are seen in the Tibetan Plateau and southeastern China, where the intensity of RV20 will increase by
more than 15.0% and 20.0% in the 1.5°C and 2°C warmer climates, respectively. Compared with the 1.5°C warmer climate, the effects of the temperature overshoot are also not uniform and are not statistically significant at the 10% significance level in most parts of East Asia (figures 3(f) and (g)). However, at local scales, stronger extreme precipitation events are seen in parts of southeastern China, southern Japan, the Korean Peninsula and western Mongolia.

To quantitatively measure regional differences in the responses, we compared the regional mean frequency of present-day RV20 and find an increase in all subregions (figure 4(a)). Among the four subregions, the increasing magnitudes of RV20 are smallest in Mongolia. In China, the Korean Peninsula and Japan, the frequency of present-day RV20 will increase by more than 100% and 140% in the 1.5°C and 2°C warmer climates, respectively.

We further used the cumulative density functions (CDFs) to estimate regional aggregated changes similar to the approach of Fischer and Knutti (2014) (figure 4(b)). Individual grid cells are weighted by their area. The CDFs indicate the fraction of land area aggregated over East Asia that experiences certain changes. The frequency of present-day RV20 will increase by more than 170% and 210% over about a quarter of the East Asian landmass in the 1.5°C and 2°C warmer climates, respectively.

We also examined changes in the intensity of RV20 (figures 4(c) and (d)). China, the Korean Peninsula and Japan see increases in intensity of about 12% and 16% under the 1.5°C and 2°C warmer climates, respectively. The corresponding increase in Mongolia is about 3% and 6% (figure 4(c)). An increase of magnitude larger than 20% and 25%, respectively, is seen in a quarter of East Asian landmass (figure 4(d)).

Does an overshoot above 1.5°C matter in terms of damaging extreme precipitation events? For China, a slight overshoot in the mid-21st century does not lead to evident differences in extreme precipitation compared with the 1.5°C warmer climate in terms of the regional mean (figures 4(a) and (b)). In Mongolia, the Korean Peninsula and Japan, the temperature overshoot generally enhances the frequency and intensity of these extreme

Figure 4. (a) Regional mean relative changes in the frequency of present-day (1986–2005) 20-year return period event in the 1.5°C, 1.5°C OS_M, 1.5°C OS_E and 2°C climates. The lines represent the multimember mean, and the boxes represent the range between two standard deviations. (b) CDFs for regional aggregated changes in frequency of present-day 20-year return period event in the 1.5°C, 1.5°C OS_M, 1.5°C OS_E and 2°C climates. Subplots (c) and (d) correspond to subplots (a) and (b), but for the intensity of 20-year return period event. The shaded areas represent the range of one standard deviation across members and the lines represent the multimember mean.
precipitation events, although with large projection uncertainty. The multimember mean values are comparable with those in the 2 °C warmer climate in Mongolia and the Korean Peninsula in the mid- and end-21st century (figures 4(a) and (c)). For Japan, the regional mean changes in the frequency and intensity of extreme precipitation are larger in the 1.5 °C OS_E climate than in the 1.5 °C warmer climate (figures 4(a) and (c)). This suggests that even a slight temporary overshoot above 1.5 °C may cause more frequent and stronger extreme precipitation events in these subregions.

### 3.2.2. Avoided impacts by the 1.5 °C never exceed scenario

We chose three typical indices along with the intensity and frequency of RV10 and RV20 to characterize extreme precipitation changes in East Asia in the warmer climates and the extreme precipitation increases that are avoided if the global warming is controlled well below 1.5 °C. The results show that all indices will increase in all subregions of East Asia, to a greater extent than SDII (figures 1 and S4).

We used equation (1) to quantify the impacts avoided if the global warming is controlled well below 1.5 °C (figures 5(a)–(c)). Compared with the 2 °C warmer climate, the 1.5 °C warmer climate avoids 26%–31% of the increase in the frequency and intensity of extreme precipitation in East Asia, with the maximum reductions occurring in Japan (38%–54%), according to most indices (figure 5(c)).

The temperature overshoot will affect regional mean extreme precipitation in Mongolia, the Korean Peninsula and Japan in both the mid- and end-21st century (figures 5(a)–(b)). In the mid-21st century, over 25% of the increase in the frequency and intensity of extreme precipitation will be avoided in Mongolia and the Korean Peninsula if there is no temperature overshoot (figure 5(a)). The temperature overshoot can even lead to comparable increase in the most extreme precipitation events as in the 2 °C warmer climate in Mongolia, the Korean Peninsula and Japan in the end-21st century (figures 5(b) and (c)). More than 25% of the increase in the frequency and intensity of extreme precipitation will be avoided in these regions in the end of the 21st century if there is no temperature overshoot according to most indices (figure 5(b)).

Changes in precipitation indices are not uniform over East Asia (figures 3 and S5). The fraction of landmass over which the increases in index values are greater than in the 1.5 °C warmer climate is also examined.
identify areas that would benefit from achieving the 1.5 °C warming target (figures 5(d)–(f)). Over four-fifths of the East Asian landmass will be relieved from additional impacts caused by the 2 °C warming if global warming is controlled below 1.5 °C, according to all the extreme precipitation indices (figure 5(f)). Over 70% of the Korean Peninsula will experience more intense and frequent extreme precipitation in 1.5 °C OS_M climate compared with the 1.5 °C warmer climate (figure 5(d)). Most indices indicate that temperature overshoot will lead to more and stronger extreme precipitation events over 80% of Japan and the Korean Peninsula in the end-21st century (figure 5(e)).

### 3.3. Moisture budget analysis for the changes in extreme precipitation

The above results show that the patterns of change in extreme precipitation are similar to those for mean precipitation, but with larger magnitudes of change. Changes in annual precipitation are dominated by summer precipitation and extreme precipitation over East Asia occurs mainly during summer. Thus, to further understand the physical processes that contribute to projected changes in summer precipitation, a moisture budget analysis was performed (equation (3)). The relative contributions of horizontal and vertical moisture advection to the projected summer precipitation changes and the associated changes of surface evaporation are shown in figure 6.
Regional mean surface evaporation over East Asia will enhance in the four warmer climates, positively associated with increased precipitation (figure 6(a)). Vertical moisture advection is the key factor responsible for the increase in precipitation-minus-evaporation (P—E). Vertical moisture advection was further separated into a dynamic component associated with changes in atmospheric circulations and a thermodynamic component associated with changes in specific humidity. Both components contribute to the area-averaged changes in P—E over East Asia in the warmer climates. Moreover, the thermodynamic component is positively associated with global warming, i.e., larger thermodynamic increases are seen for warmer climates. Changes in the dynamic component are comparable in the 1.5 °C and 2 °C warmer climates, and are larger than those in the 1.5 °C OS_M and 1.5 °C OS_E climates. This indicates that a temperature overshoot might modulate large-scale circulation, and further precipitation.

The area-averaged moisture budget for precipitation changes over China is like that for changes over the whole of East Asia (figures 6(a) and (b)). Enhanced surface evaporation is the main contributor to changes in precipitation over Mongolia in the four warmer climates (figure 6(c)). Mean summer precipitation changes over the Korean Peninsula are comparable in the four warmer climates, unlike the case of extreme precipitation (figures 4 and 6(d)). One possible reason for this difference is that extreme precipitation is affected more by thermodynamics (i.e., global warming) than mean precipitation, and it may also be affected by the large projection uncertainty for small regions. The vertical moisture advection is also the main contributor to the P—E changes in Korean Peninsula (figure 6(d)). The precipitation changes in Japan are comparable in 1.5 °C OS_E and 2 °C warmer climates (figure 6(e)). Compared with the 1.5 °C OS_E climate, the thermodynamic component is larger while the dynamic component is smaller in the 2 °C warmer climate. In addition, the area-averaged moisture budget for precipitation changes over South China (22°N to 33°N, 105°E to 122°E) is also investigated. The relative contributions of the moisture budget components of precipitation changes in South China are similar to East Asia, but with larger magnitudes (figure 6(f)).

In summary, vertical moisture advection is the main contributor to changes in P—E over East Asia in the warmer climates. The thermodynamic component is positively associated with global warming. Changes in dynamic component differ among the four warmer climates. The temperature overshoot might modulate large-scale circulations, and further precipitation.

As shown above, vertical moisture advection is the main contributor to the changes in P—E over East Asia except for Mongolia. The patterns of its dynamic and thermodynamic components are further analyzed (figure 7). Compared with present day, changes in the thermodynamic component are relatively uniform over East Asia in the 1.5 °C warmer climate (figure 7(a)). The differences between the three other warmer climates and the 1.5 °C warmer climate are also uniform over East Asia (figures 7(b)–(d)). Compared with the thermodynamic component, the dynamic component has more noticeable regional and local characteristics (figures 7(e)–(h)), and its patterns of change are similar to those of SDII and the extreme precipitation indices (figures 3, S1 and S5).

To further understand the thermodynamic and dynamic background, changes in the summer low-level circulation and humidity were investigated (figure 8). The atmospheric moisture content will increase under the global warming. In the 1.5 °C warmer climate, the southwesterlies over South China are stronger than those in the present day, leading to more precipitation in this region (figure 8(a)). Besides, the cyclonic circulation changes over Japan and Korean Peninsula may contribute to the more precipitation increase in these regions. There is a cyclonic circulation difference over South China and Japan between the 2 °C and 1.5 °C warmer climates, which is consistent with the larger dynamic contributions in these regions in the 2 °C warmer climate compared with the 1.5 °C warmer climate (figures 7(h) and 8(d)). There are few evident low-level circulation differences over East Asia between the 1.5 °C OS_M and 1.5 °C warmer climates (figure 8(b)). An evident cyclonic circulation difference occurs over Japan between the 1.5 °C OS_E and 1.5 °C warmer climates (figure 8(c)). This is consistent with the larger changes in the dynamic component over Japan in the former climate compared with the latter.

4. Summary and concluding remarks

The changes in extreme precipitation over East Asia at the stabilized 1.5 °C and 2 °C warming levels, as well as the avoided impacts by the half a degree less warming were investigated using the NCAR CESM low-warming dataset. Whether a temporary temperature overshoot should be allowed from the perspective of extreme precipitation was also investigated. The main findings are summarized as follows:

1. Annual SDII will increase significantly in most parts of East Asia in the 1.5 °C and 2 °C warmer climates. The temperature overshoot will not lead to significantly stronger SDII in most parts of East Asia in comparison with the 1.5 °C warmer climate. Patterns of changes in SDII differ among the seasons.
(2) Dry (wet) days will decrease (increase) in most parts of East Asia in the warmer climates. The intensity and frequency of all precipitation percentiles will increase in the warmer climates, with larger magnitudes in extreme precipitation than in moderate and light precipitation. Among the subregions analysed here, increases in the frequency and intensity of extreme precipitation are greatest in China and Japan.
The RV10 and RV20 were used as indicators of rainstorm flood disasters. In China, the Korean Peninsula and Japan, the frequency of present-day RV20 will increase more than 100% and 140% in the 1.5 °C and 2 °C warmer climates, respectively. The temperature overshoot will not lead to significantly stronger RV10 and RV20 in most parts of East Asia in comparison with the 1.5 °C warmer climate on the local scale. However, in Mongolia, the Korean Peninsula and Japan, the temperature overshoot generally enhances the frequency and intensity of these extreme precipitation events in terms of regional mean, although with large projection uncertainty.

In comparison with the 2 °C warmer climate, the 0.5 °C less warming in the 1.5 °C warmer climate will help avoid 26%–31% of the increase in different extreme precipitation indices in East Asia, with the greatest reductions (38%–54%) in Japan. More than four-fifths of the East Asian landmass will face more frequent and intense extreme precipitation events with an additional 0.5 °C of warming.

The impacts of a temperature overshoot are seen in Mongolia, the Korean Peninsula and Japan in terms of regional mean. More than 25% of the increase in the frequency and intensity of extreme precipitation will be avoided in these regions during the end of the 21st century, according to the best estimate.

Vertical moisture advection is the main contributor to the increase in P—E in the four warmer climates over East Asia, except for Mongolia. Changes in the thermodynamic component are relatively uniform over East Asia and are positively associated with warming, whereas changes in the dynamic component have more regional and local characteristics. A temperature overshoot might modulate large-scale circulation, and further precipitation. Increased low-level specific humidity and cyclonic circulation changes might explain the larger increases in precipitation over South China and Japan.

Several methods and models, including the stand-alone AGCM simulations of the HAPPI project (Lee et al 2018), the transient projection of CMIP5 models (Li et al 2018d, Zhou et al 2019) and regional climate model downscaling (Li et al 2018a, Li et al 2018c), have been used in analyzing the East Asian extreme precipitation changes under the 1.5 °C and 2 °C warming targets. While the results are qualitatively consistent in projecting an increase in the frequency and intensity of extreme precipitation in the context of regional average, quantitative
differences are evident on regional and local scales among the different methods. Differences are also seen in positions of hotspots of the responses (cf. figures 1–3 of Zhou et al 2019 with figures 1, 3 and S5 of this study). The uncertainty in the projected changes arising from different methods and simulations must be considered in regional adaptation activities. In addition, no previous study has investigated the impacts of temperature overshoot on East Asian climate in terms of extreme precipitation. Our analyses do indicate that a temperature overshoot will lead to more frequent and intense extreme precipitation in Mongolia, Korean Peninsula and Japan in terms of regional mean in both the mid- and end-21st century.

Finally, we acknowledge the following limitations of this study. The results of only one set of coupled low-warming simulations may include uncertainty in the projection. The model dependence of the results presented here warrants further investigation. In addition, aerosol emissions, which have a large impact on the climate over East Asia, do not vary among the three low-emission scenarios in this study. This should also be considered in future work. Moreover, low-resolution global models have limitations in exploring extreme precipitation at regional scales, particularly over complex terrain. Convection-permitting models are recommended and hoped to be used in future studies of extreme precipitation (Rasmussen et al 2017, Berthou et al 2018).

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