Understanding the sensitivity of hourly precipitation extremes to the warming climate over Eastern China

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Abstract

Theoretically, under the warming climate, due to the increase of the atmospheric water vapor, the precipitation extremes would increase. The Clausius-Clapeyron (CC) scaling indicates an increase of precipitation extremes at a rate of about 7% globally. However, the response of precipitation extremes to global warming is complex globally. In this study, we investigated the hourly precipitation extremes-dew-point temperature scaling relation in eastern China and the theoretical explanation. It is shown here that the hourly precipitation extreme intensity increases with the dew-point temperature (DPT), following the CC scaling rate. Conversely, as DPT exceeds ~22 °C, the negative scaling exists, particularly for the southern part of China. The change in the scaling direction as the DPT exceeds 22 °C may be attributed to the negative scaling of precipitation efficiency/vertical velocity with DPT. The increase in the convective inhibition and decrease in the temperature advection above ~22 °C, partially explain the negative scaling of precipitation efficiency and vertical velocity with DPT. Our results may help understanding the variations in precipitation extremes under future warming.

1. Introduction

The variation of precipitation extremes due to anthropogenic climate change is of great concern for the society (Liu et al. 2009, Zhang et al. 2013, Drobinski et al. 2016, Prein et al. 2017, Baker et al. 2018). It is generally agreed that the warming climate could modify precipitation characteristics in terms of the amount, frequency and intensity (Min et al. 2011, Prein et al. 2017, Huang et al. 2019). However, the understanding of the essential physical linkage between precipitation extremes and global warming remains room for improvement (Westra et al. 2014, Visser et al. 2020).

The quantitative relationship between precipitation extremes intensity and temperature, termed as 'scaling', is theoretically linked to the Clausius–Clapeyron (C–C) equation which predicts roughly a 7% (C–C scaling) increase in the daily precipitation extremes associated with atmospheric warming (Trenberth et al. 2003, Pall et al. 2007, Bui et al. 2019). The scaling rates vary in different climate regions based on the selection of temperature (surface air temperature or dew-point temperature) or the temporal-scale of precipitation events (5-mins, hourly or daily precipitation datasets) (e.g., Panthou et al. 2014). Generally, observations, reanalysis datasets and climate model simulations report a variety of scaling rates between precipitation extremes and temperature, including super C–C scaling in Europe (Lenderink and Van Meijgaard 2008, 2010, Berg et al. 2013, Schroer and Kirchengast 2018) but lower C–C scaling in North America (Mishra et al. 2012, Lepore et al. 2015). At the higher temperatures, negative scaling has been revealed in many region over the Globe (Utsumi et al. 2011, Wasko et al. 2016, Bui et al. 2019), particularly in the tropics (Maeda et al. 2012, O’Gorman 2012, Drobinski et al. 2016, Wang et al. 2017, Wasko et al. 2018, Yin et al. 2018).

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Many factors have contributed to the departure from C–C scaling, such as, temporal and spatial scales, the selection of temperature scaling variable (Bui et al 2019), the precipitable water and vertical velocity (Kunkel et al 2020), dynamical conditions (Drobinski et al 2016), and the precipitation types (Berg et al 2013). Particularly for the negative scaling of daily precipitation extremes on temperature exceeding ∼25 °C, it may be due to seasonal effects (Berg et al 2009), moisture limitations (Hardwick Jones et al 2010), duration of precipitation events (Utsumi et al 2011, Wasko et al 2015), cooling effect (Bao et al 2017), storm type (Molnar et al 2015), the decrease in relative humidity (Barbero et al 2018), intermittency of rainfall at higher temperature (Schleiss 2018), the sampling of precipitation and temperature (Visser et al 2020), etc. Thus, the causes of the complexity of the scaling relationship between the precipitation extremes and temperature remains highly debated. Particularly, the scaling rate of extreme precipitation with future warming is not spatially and seasonally uniform (Tabari et al 2019, Tabari 2021). This might due to the spatially and seasonally varying contributions of dynamic and thermodynamic factors.

Dominated by the Asian monsoon system, eastern China is very vulnerable to climate extremes (Zhai et al 1999, 2005, Zhou et al 2009, Wang et al 2012). The related studies have focused on the definitions and tendency of the precipitation extremes, the controlling large-scale circulations, the projections of future precipitation intensities, detection of human influence (Sun and Ao 2013, Zhou et al 2014, Chen and Sun 2021), etc. Recently, the warming rate in China is fast, comparing to other regions. Understanding the precipitation extremes to the warming climate is an urgent problem. Studies have gradually noticed the importance of the precipitation extremes–temperature relationship. Some analysis have focused on some specific regions, as South China (Sun et al 2013) and Anhui Province (Huang et al 2017). Due to the significant regional discrepancies in the precipitation extremes, Miao et al (2016) and Guo et al (2020) have enlarged the study regions. These results show

Figure 1. The distribution of the 2420 stations used in this study (a), and dependency of different percentiles of hourly precipitation extremes on daily mean temperature using station data (b), and ERA5 reanalysis datasets (c) in the period of 1991–2012 in eastern China. The red, blue, purple and orange dots in (a) are for NEC, NC, YHRB and SC, respectively. Four sub-regions over eastern China: Northeastern China (NEC, 110°–135°E, 43°–54°N), North China (NC, 110°–122°E, 34°–43°N), Yangtze-Huaihe River Basin (YHRB,110°–122°E, 28°–34°N), South China (SC, 110°–122°E, 20°–28°N). Scatter points in (b), (c) are computed from certain percentiles in each temperature bin. Solid curves are computed by the 4th degree exponential polynomial-fitting of precipitations. Colorful scatters and lines are for the different percentiles. Note the logarithmic Y-axis. Each dot in (b) and (c) means the logarithmic hourly precipitation for a certain station and a certain year in four sub-regions from station data and sub-regional mean for a certain year from ERA5 reanalysis datasets, respectively.
the scaling of precipitation extremes with temperature have ranged from three times the CC-scaling, two times the C-scaling, and CC-scaling to sub-CC, which infers the complex relationship between precipitation extremes and temperature over China. More importantly, there is currently only limited research on the theoretical explanation on the sensitivity of extreme rainfall in eastern China to temperature, particularly for the dynamic and thermodynamic factors.

In this study, we examined the C–C scaling in the relationship between the extreme hourly precipitation intensity and temperature across eastern China and investigated the theoretical explanation, from the perspective of dynamic and thermodynamic aspects. In particular, we aimed to answer the following two questions: (1) Does the hourly precipitation extremes of different sub-regions in eastern China scale with temperature following the C–C scaling? (2) If it deviates from the C–C scaling, how to understand the physical factors of deviation?

2. Data and methods

We obtained the hourly precipitation and daily mean air temperature of 2420 quality-controlled stations (figure 1(a)) over China during the period of 1991–2012 provided by China Meteorological Administration. The hourly variables of mean temperature, dew-point temperature, total precipitation, total column water vapor, 500 hPa- vertical velocity, 500 hPa- zonal wind, 500 hPa- meridional wind, 500 hPa- temperature and the convective inhibition (CIN) in the period of 1991–2012 from the ERA5 reanalysis datasets (~0.25° × ~0.25°) (Hersbach et al. 2020) have also been used, since the datasets have good ability to describe the East Asian summer monsoon (Huang et al. 2016) and can be used to understand the relation between precipitation extremes and daily mean temperature (Huang et al. 2019). Particularly, we focused four sub-regions of eastern China (figure 1(a)): Northeastern China (110°–135°E, 43°–54°N), North China (110°–122°E, 34°–43°N), Yangtze-Huaihe River Basin (110°–122°E, 28°–34°N), and South China (110°–122°E, 20°–28°N).

To analyze the dependence of hourly precipitation extremes on temperature, we first picked the non-zero value of hourly precipitation and the corresponding daily mean temperature (or hourly dew-point temperature). According to this temperature-precipitation pairing, grouping is based on temperature and divided into 20 bins of equal size temperature brackets. Consistent with previous similar studies (Lenderink and Van Meijgaard 2008, Huang et al. 2019), to investigate different-intensity precipitation extremes, the 90%–95% and 95%–99% of the distribution in each bin of precipitation events have been calculated, and the resulting data points have been used to perform a 4th degree exponential polynomial-fitting.

In fact, we have verified the ability of the ERA5 reanalysis of capturing the relation between hourly precipitation extremes and daily mean temperature using ERA5 reanalysis and station-based observations. The results show that as the daily mean temperature is below ~25°C, the hourly precipitation extremes increase with the rise of daily mean temperature. The rate is slightly higher than the C–C scaling (7%). The negative scaling is also found in eastern China and is particularly associated with the higher temperatures (≥~25°C). This behavior is robust throughout the domain for the extreme percentiles (90%–95%, 95%–99%). Similarly, the ERA5 reanalysis also shows the out-of-phase relation between the hourly precipitation extremes and daily mean temperature, with a changing temperature of ~25°C, although less decreases rate still exists in the ERA5 reanalysis datasets than that in station-based observations (figure 1(c)). Thus, the ERA5 reanalysis can capture the relation between the hourly precipitation extremes and daily mean temperature in eastern China.

Since daily mean temperatures can decrease during a rainfall event (Bao et al. 2017), it may partially affect the temperature-precipitation relation. To overcome this shortage (Bui et al. 2019), we chose the hourly dew-point temperature, which is a better and more realistic metric for the responses of precipitation extreme to temperature increases (Ali and Mishra 2017, Zhang et al. 2019, Ali et al. 2021). Thus, in the following, we analyzed the scaling of hourly precipitation extremes with hourly dew-point temperature in boreal summer using the ERA5 reanalysis.

To understand the deviations of CC-scaling, we chose the concept model of precipitation extremes introduced by Doswell et al. (1996), as

\[
P \propto Ewq\tag{1}\]

where \(P\) is the precipitation rate, \(E\) is the precipitation efficiency, \(w\) is the vertical velocity, \(q\) is the mixing ratio of air. The mid-tropospheric vertical velocity is commonly used in precipitation extreme scaling (Emori and Brown 2005, Gorman et al. 2009), thus, we chose vertical pressure velocity at 500 hPa (W500) as \(w\) in equation (1).

Precipitation efficiency measures the percentage of moisture in the air converting into precipitation. In this study, we defined the precipitation efficiency as the ratio of the hourly surface rain rate to the sum of the hourly surface evaporation and vertically integrated moisture convergence (Sui et al. 2007, 2020) based on the hydrometeor budget. The precipitation efficiency is an useful concept for estimating heavy rainfall under a given
environmental condition (Huang et al 2019). The concept model has the advantages to understand the role of precipitation efficiency rather than the other model which is established by vertical motion and moisture condition (Pfahl et al 2017, Ali and Mishra 2018).

Equation (1) indicates that if a significant precipitation rate is to be formed, the rising air should have a substantial water vapor content and a rapid ascent rate. Differentiating the concept model (1) with respect to a temperature \(T\) gives,

\[
\frac{\partial P}{\partial T} = q.w. \frac{\partial E}{\partial T} + q.E. \frac{\partial w}{\partial T} + w.E. \frac{\partial T}{\partial T}
\]  

(2)

The changes in precipitation efficiency and vertical velocity with temperature could partially explain the departures from C–C scaling, by equation 2.

3. Results

3.1. Examining the scaling of hourly precipitation extremes with dew-point temperature

Figure 2 shows the dependency of different percentiles of hourly precipitation extremes on hourly dew-point temperature in four sub-regions over eastern China using the ERA5 reanalysis datasets. Generally, in the four sub-regions, as the hourly dew-point temperature is below \(\sim 22^\circ C\), the hourly precipitation extremes increase with the rise of dew-point temperature. The rate is slightly higher than the C–C scaling (7%) but does not reach a super C–C scaling (\(\sim 14\%\)) (Lenderink and Van Meijgaard 2010, Schroer and Kirchengast 2018). This also suggests the complexity of the relation in different regions (Drobinski et al 2016). Similar to the results in many regions across the world, the negative scaling is also found in eastern China and is particularly as the higher dew-point temperature (\(\sim 22^\circ C\)). This behavior is robust throughout the domain for the extreme percentiles (90%–95%, 95%–99%). In fact, this is also robust for the percentiles above 70% in eastern China (Huang et al 2019) and the percentiles between 20%–80% in the French Mediterranean region (Drobinski et al 2016).
We should also notice the scaling relation between hourly precipitation extremes and dew-point temperature exhibits regional discrepancies, generally, it can be divided into two groups: northern and southern part of China. In the northern part of China (NEC figure 2(a) and NC figure 2(b)), the dominant pattern is the hourly precipitation extremes increase with the rise of dew-point temperature, while in the southern part of China (YHRB figure 2(c) and SC figure 2(d)), the negative scaling as hourly dew-point temperature exceeds ∼22°C is obvious and with a high rate of the decreasing slope.

Overall, in eastern China, the ERA5 reanalysis datasets indicate that as hourly dew-point temperature below ∼22°C, the hourly precipitation extremes increase with the rise of dew-point temperature, almost following the rate of the C–C scaling, ∼7%, particular for the northern part of China. The negative scaling is visible as hourly dew-point temperature exceeds ∼22°C. The hourly precipitation extremes decrease with hourly dew-point temperature increases, particularly for the southern part of China. The threshold point at high-latitude regions tends to be much lower compared with low-latitude region.

3.2. Understanding the scaling of hourly precipitation extremes with dew-point temperature
To understanding the out-of-phase relationship between hourly precipitation extremes and dew-point temperature, we have analyzed $\frac{\partial E}{\partial T}$ and $\frac{\partial q}{\partial T}$ described in equation 2 respectively (figure 3). The dependency of different percentiles of hourly precipitation efficiency and dew-point temperature (figures 3(a)–(d)) shows quite consistent results in that between hourly W500 and dew-point temperature (figures 3(e)–(h)) in the four sub-regions. Results show that, in Northeastern China, the precipitation efficiency is quite stable (figure 3(a)), while the W500 (figure 3(e)) increases slightly as the dew-point temperature increases. In North China
and Yangtze-Huaihe River Basin (figures 3(c), (g)), the precipitation efficiency and W500 increases as the dew-point temperature rises. As the dew-point temperature exceeds ~22 °C, the precipitation efficiency and W500 sharply decrease, especially in the Yangtze-Huaihe River Basin. In South China, both of the precipitation efficiency and W500 decrease, as the dew-point temperature increases. These relations are comparable to the relationship between the hourly precipitation extremes and dew-point temperature (figure 2).

On the other hand, as expected, governed by the C–C equation, the atmospheric moisture increases with dew-point temperature following the C–C scaling (figures 3(i)–(l)). The C–C scaling can largely explain the relation between hourly precipitation extremes and dew-point temperature below a certain temperature (~22 °C). As

Figure 4. Dependency of hourly precipitation efficiency (unit: %) on convective inhibition (a), CIN, unit: J kg⁻¹ and hourly vertical velocity at 500 hPa (unit: 10⁻³ m/s⁻¹) on temperature advection at 500 hPa (f), unit: 10⁻³ m/s⁻¹ in eastern China, and the dependency of different percentiles of hourly CIN (b)–(e), unit: J kg⁻¹ and hourly temperature advection at 500 hPa (g)–(j), unit: 10⁻³ m/s⁻¹ on hourly dew-point temperature in NEC (c), (d), NC (e), (f), YHRB (g), (h) and SC (i), (j) using ERA5 reanalysis datasets in the period of 1991–2012. Solid curves are computed by the 4th degree exponential polynomial-fitting.
dew-point temperature exceeds this temperature, the reverse relation may be partially due to the negative relation between the precipitation efficiency (vertical motion) and dew-point temperature.

To investigate the possible factors of the precipitation efficiency, we further analyzed the changes of the convective inhibition (CIN) and temperature advection to DPT. The precipitation efficiency is negatively correlated with CIN (Market et al. 2003), which is also confirmed in eastern China (figure 4(a)) and four sub-regions (figure not shown). The relation between the hourly CIN and dew-point temperature in four sub-regions is shown in figure 4(b)–(e). In Northeastern China (figure 4(b)), the hourly CIN slightly decreases with the increase of the dew-point temperature. In North China (figure 4(c)) and Yangtze-Huaihe River Basin (figure 4(d)), when the dew-point temperature is lower than ∼22 °C, the hourly CIN decreases as the dew-point temperature increases. The decrease in CIN corresponds to the increase in the precipitation efficiency. Therefore, the hourly precipitation extremes increase as the dew-point temperature rises. Particularly, when the dew-point temperature exceeds ∼22 °C, the hourly CIN in Yangtze-Huaihe River Basin (figure 4(d)) and South China (figure 4(e)) significantly increase with the rise in dew-point temperature. The significant increases in CIN at high dew-point temperature would favor the decrease in the precipitation efficiency, thus leading to the decrease in the hourly precipitation extremes. Globally, Chen et al. (2020) has also revealed that under global warming, the CIN has enhanced over most land. It may be traced to a higher lifting condensation level and a higher level of free convection and thus more negative buoyancy.

The positive correlation between the vertical velocity and temperature advection (− ∇ · VT) has been established by the quasi-geostrophic omega equation. The warm advection favors the ascending motion, and vice versa. This positive relation is investigated in eastern China (figure 4(f)) and found in sub-regions (Figure not shown). Similarly, we further analyzed the relation between the hourly temperature advection and dew-point temperature in the four sub-regions (figure 4(g)–(j)). As the dew-point temperature rises, the hourly temperature advection in Northeastern China is quite stable (figure 4(g)), while in North China it increases strongly (figure 4(h)). In YHRB (figure 4(i)), the hourly temperature advection increases as the dew-point temperature rises. However, as the dew-point temperature exceeds ∼22 °C, the hourly temperature advection significantly decreases as the dew-point temperature rises, particularly in South China (figure 4(j)) and YHRB (figure 4(i)). Due to the positive relation between the vertical velocity and temperature advection, this negative slope between the temperature advection and the dew-point temperature will contribute to that between the vertical velocity and dew-point temperature.

4. Conclusion and discussion

Analyzing the hourly precipitation extremes-temperature scaling relation may help understand the variations in sub-daily precipitation extremes under the warming future. In this study, we examined the applicability of the
C–C scaling in explaining the relation between the hourly precipitation extremes and dew-point temperature in eastern China.

As summarized in figure 5, we found that as the hourly dew-point temperature is below the threshold point (\(\sim -18 \, ^\circ \text{C} - 20 \, ^\circ \text{C}\) for the northern part of China and \(\sim -22 \, ^\circ \text{C}\) for the southern part of China), the hourly precipitation extremes increase as the dew-point temperature rises, with a rate of the C–C scaling (7%). This increase rate can be partially explained by the relation between the water vapor and dew-point temperature, following the C–C scaling. As the dew-point temperature exceeds the threshold point, deviated from the C–C scaling, a negative scaling is displayed between hourly precipitation extremes and the dew-point temperature, particularly in the southern part of China. This negative scaling can be traced to the hourly precipitation

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**Figure 6.** Same as figure 2, but for dependency of different percentiles of hourly convective precipitation (left panels) and large-scale precipitation (right panels) on hourly dew-point temperature in NEC (a), NC (b), YHRB (c) and SC (d) using ERA5 reanalysis datasets in the period of 1991–2012.
efficiency, and vertical velocity decrease as the dew-point temperature rises. Particularly, the increase in the convective inhibition and the decrease in the temperature advection can partially explain the negative scaling of precipitation efficiency and dew-point temperature, vertical velocity and dew-point temperature exceed the threshold point, respectively.

Several questions still remain and need further analysis. We should also notice obvious regional distinctions (northern and southern part of eastern China), which may be caused by the large-scale circulations, different types of precipitation extremes (Singh and O’Gorman 2014). Figure 6 shows the dependency of the hourly convective precipitation and large-scale precipitation extremes on hourly dew-point temperature in the four sub-regions. Interestingly, the out-of-phase relation does not exist in the convective precipitation extremes-temperature relation. Instead, the intensity of hourly convective precipitation extreme increases with the hourly dew-point temperature in the four sub-regions (figure 6, left panels). The hook shape is visible in the large-scale precipitation extremes and temperature relation (figure 6, right panels), which is similar as that between the total precipitation extreme intensity and dew-point temperature (figure 2). These infer that the out-of-phase relation between the total precipitation extremes and dew-point temperature is mostly traced to that between the large-scale precipitation extremes and dew-point temperature. This may be associated with the character of different precipitation extremes. The different kinds of precipitation efficiency (e.g., large-scale precipitation efficiency and cloud microphysics precipitation efficiency), should also be separated for different types of precipitation extremes to investigate the physical mechanisms of different scaling, in our following work. These should be carefully evaluated to make reliable projections for different climatic zones under a warmer future.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI:https://doi.org/10.1002/qj.3803.

Conflict of interest

The authors declare that they have no conflict of interest.

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