Role of Convective Precipitation in the Relationship between Subdaily Extreme Precipitation and Temperature

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(Manuscript received 8 February 2017, in final form 19 August 2017)

ABSTRACT

On a subdaily time scale, the intensities of extreme precipitation are observed to increase with temperature at a rate exceeding water vapor constraints determined by the Clausius–Clapeyron (C-C) relationship. This so-called super C-C scaling has been suggested to occur as a result of 1) the statistical effect that involves the transition of precipitation types from stratiform to convective events and 2) the physical effect by which the convective process itself can overcome the thermodynamic limitation. This study examines these two mechanisms for the super C-C relationship using in situ observations in South Korea for a recent 35-yr period, focusing on the role of convective rainfall. Scaling results show that hourly extreme precipitation undergoes a transition from a C-C rate to a super C-C rate at around 20°C, supporting the statistical effect. The transition temperature observed in South Korea is, however, much higher than in European regions (12°C), which seems to be due to the climatologically lower frequency of convective events in South Korea than in Europe. Nevertheless, the threshold fraction of convective precipitation when the scaling transition starts to occur is found to very similar between two regions, around 0.2, indicating the important role of convective events in shaping the scaling. On the other hand, convective extreme precipitation alone exhibits a super C-C scaling, suggesting that the physical effect is also at work in South Korea. Also, the scaling shows a robust peaklike shape with maximum precipitation intensity near 24°C, which is closely linked with moisture limitation at high temperature, supporting the previous findings.

1. Introduction

The intensity of extreme precipitation is expected to increase with temperature at a rate consistent with the available moisture, which is determined by the Clausius–Clapeyron (C-C) relation. The C-C rate is approximately 6%–7% °C⁻¹ and is found to largely hold for observations and model simulations (Allen and Ingram 2002; Trenberth et al. 2003; Westra et al. 2013; Zhang et al. 2017). The scaling between extreme precipitation and temperature varies with many factors including the magnitude of extremes and the time scale. Precipitation extremes of a shorter time scale tend to be more sensitive to a temperature change. In particular, subdaily or hourly precipitation extremes exhibit enhanced scaling up to a doubled C-C rate. Such an increase in precipitation intensity that exceeds thermodynamic constraints is known as a super C-C scaling (Lenderink and van Meijgaard 2008; Berg et al. 2013).

The super C-C scaling has been observed in many regions including Europe, North America, Hong Kong, and Japan (listed in Table 1).

There are different mechanisms concerning the super C-C scaling. One is the statistical argument that the super C-C scaling results from a systematic change from large-scale to convective rainfall events (Haerter and Berg 2009; Berg and Haerter 2013). In this case, the convective and large-scale events separately both follow the C-C rate, while the resulting dependency is a super C-C scaling because of the transition between dominant precipitation types from the large-scale to convective events. The other argument is that the super C-C scaling is a property of convective events (Berg et al. 2013; Moseley et al. 2013), which involves physical feedback processes associated with increases in the convective available potential energy (CAPE) and the latent heat release with temperature (Trenberth et al. 2003; Panthou et al. 2014). Thereby, convective extreme events inherently follow a super C-C scaling and the increased contribution of convective rainfall types shifts the total scaling.
from the C-C to the super C-C rate at around 12°C (Berg et al. 2013). In addition to the super C-C scaling, many studies reported the upper limit of the scaling such that the scaling levels off or declines at high temperatures above 24°C (Table 1). This behavior is suggested to be due to the moisture limitation to the convective system at high temperatures, which can be seen from the decrease in relative humidity or the stabilized scaling obtained when using dewpoint temperature (Hardwick Jones et al. 2010; Lenderink et al. 2011; Panthou et al. 2014; Westra et al. 2014).

Hence, this study aims to examine the subdaily precipitation–temperature relationship in South Korea and to investigate the contribution of convective precipitation to the scaling pattern. This paper is organized as follows. Section 2 includes a discussion of the observations and a description of the scaling methodology used for the analysis. The results are presented in section 3, followed by a summary and conclusions in section 4.

2. Data and methods

We used surface observations of temperature, precipitation, humidity, pressure, and cloud type from 26 stations during 1980–2014, provided by the Korea Meteorological Administration (KMA). First, we selected 26 stations out of the total 60 stations available, which had less than 10% missing data during the 35-yr period (Fig. 1). Basic and extended quality checks were performed for KMA data (KMA 2016a) based on the World Meteorological Organization (WMO) guide (WMO 2010) and other methods (Durre et al. 2010). The plausible value check and internal consistency check were commonly applied to all variables analyzed in this study. In addition, the time consistency check was carried out for temperature and humidity, and the Automated Meteorological Data Acquisition System (AMeDAS) and Madsen–Allup checks for precipitation. Two stations (Gwangju and Mokpo) experienced station relocation during the analysis period (KMA 1995), but its influence was assessed to be negligible on the homogeneity of temperature and precipitation (Jung et al. 2002; Ryoo et al. 2006; Chang and Kwon 2007). The selected stations are also relatively homogeneous with similar observation heights.
Fig. 1. (a) Locations of stations (black dots) and temperature ranges (color coded) of each station from minimum (left box) to maximum (right box). In addition to temperature (daily), precipitation (hourly), cloud types (most dominant cloud; 3-hourly), relative humidity (daily), and surface pressure (daily) data were collected from all 26 stations. Data depicted in the Korea Peninsula means results were obtained when using data from all stations. (b) Number of stations having data in each temperature bin for different time scales. Shading indicates the selected temperature range (8°–28°C) which covers more than 20 stations (>80%).
except one station (Daegwallyeong located at 700 m above sea level), having similar temperature ranges for the use of the scaling calculation (Fig. 1). Thus, all data from 26 stations were pooled together for each variable in one dataset, corresponding to approximately 900 years, representing South Korea. Then, the precipitation percentiles were computed using the dataset conditional on the temperature (see below for details). Hourly precipitation was accumulated to compile longer duration time series (from hourly to daily). Dewpoint temperatures were also used to check the robustness of the overall scaling patterns and assess the effect of moisture limitation at high temperatures.

The monsoon season (April–October) was selected because other seasons experience precipitation in the form of snow, which may have a different response to temperature (O’Gorman 2014; Lute et al. 2015). Tropical cyclones generated in low latitudes bring extensive moisture and precipitation to East Asia in the boreal summer (e.g., J.-Y. Lee et al. 2017), and these external systems can affect the regional features of scaling. To minimize noise arising from typhoons, we excluded days under the influence of typhoons based on the annual report of the National Typhoon Center (KMA 2016b). About 100 typhoons affected the Korea Peninsula over approximately 300 days during the analysis period. However, there was no significant influence of typhoons on scaling owing to the relatively small number of days affected by them in comparison to the total number of wet days.

There are various methods of calculating scaling, including quantile regression (Wasko and Sharma 2014), equal-distance bins (Lenderink et al. 2011), and equal-number bins (Hardwick Jones et al. 2010), but if the sample size is large enough (>100,000 samples), the difference among the methods can be negligible (Wasko and Sharma 2014). The sample size of our study is great enough (>380,000 wet events) for this to apply. We have also compared three methods using our data and found similar results (not shown). To determine the role of convective precipitation, we used an equal-temperature distance bin method, which is useful for finding transitions in scaling (Lenderink et al. 2011; Berg et al. 2013). Following the method of Lenderink et al. (2011), we binned precipitation events based on daily mean temperature of the same station with a width of 2°C and computed the 99th, 90th, and 75th percentiles of wet events when the precipitation intensity was over 0.1 mm. To ensure smooth scaling, we made the bins overlap by 1°C to calculate the percentiles. All percentiles were computed using raw data for each temperature bin, and their 90% confidence intervals were estimated using a bootstrapping method with half of the original data following Berg et al. (2013). We used daily mean temperatures to reduce internal variability arising from temperature fluctuations even during precipitation events (Westra et al. 2014).

When using the equal distance method, the total temperature range used to compute scaling and the distribution of temperature among stations can vary considerably. To obtain robust scaling results and consider different temperature distributions across stations (Fig. 1a), we selected a fixed temperature range of 8°C–28°C, which covers more than 80% of station data, representing South Korea (Fig. 1b). The daily mean temperature in South Korea during 1980–2014 ranged from −6°C to 32°C, but only 1.5% of the days were below 8°C and 0.2% were above 28°C.

To examine influences of precipitation types and humidity on scaling features of extreme precipitation, we used observations of cloud types and humidity from 26 stations. Convective and stratiform types of precipitation were decided using 3-hourly synoptic observations of the most dominant cloud type, which were made by weather observers of the KMA. Precipitation events were classified into convective events in case of cumulus and cumulonimbus types, whereas stratiform events were related to stratus and nimbostratus types, as in Berg and Haerter (2013). This classification was made on a station basis. Then we calculated scaling for convective and stratiform events using a pooled dataset made using all stations, and results were compared with that from the entire set of events. For humidity analysis, we used daily mean value of relative humidity from all stations to reduce diurnal variability noise. Specific humidity was also computed from relative humidity, surface pressure, and temperature. Humidity was averaged over the extreme precipitation events based on the 99th percentiles at each temperature bin and compared with the results of total precipitation and also with those of no precipitation.

3. Results

The relationship between temperature and the precipitation intensity at different percentiles and on different time scales is displayed in Figs. 2a–c. To compare the characteristics of scaling conveniently, all precipitation intensities were converted into the same units (mm day$^{-1}$). The precipitation–temperature relationship in South Korea displays a peaklike structure, in which the highest precipitation intensity occurs around 24°C. This scaling pattern of precipitation intensities with an increase at low temperatures and a decrease at high temperatures is a common feature found at mid-latitudes (e.g., Utsumi et al. 2011). In addition, the
response of shorter period precipitation to temperature becomes stronger with a steeper scaling slope until the peak temperature is reached, which is consistent with results for other regions (Lenderink and van Meijgaard 2008; Hardwick Jones et al. 2010; Westra et al. 2014).

For daily mean temperatures below 20°C, the 99th percentile of hourly precipitation exhibits a temperature dependence close to the C-C rate. For temperatures higher than 20°C, this dependence increases to a doubled C-C rate, indicating a super C-C scaling. There is a clear transition from the C-C to doubled C-C scaling, whereas the transition temperature (20°C) in South Korea is much higher than that in other regions, which is around 12°C (Lenderink et al. 2011; Berg et al. 2013). Results for the 90th and 75th percentiles show increases in precipitation intensities with temperature until around 24°C, but with weaker rates than those of the 99th percentiles (Figs. 2b,c). The lower percentiles also display negative scaling above the peak temperature. Overall, more-extreme precipitation events (higher percentiles) and precipitation on a shorter time scale (hourly) exhibit larger scaling slopes. Further, hourly

Fig. 2. Dependency of precipitation intensity (logarithmic vertical scale) of different time-scale events on daily mean temperature for (a) 99th (extremes), (b) 90th, and (c) 75th percentiles. The shading indicates 90% uncertainty range derived from a bootstrapping method. Gray and black dashed lines indicate the C-C and the doubled C-C scaling, respectively. (d)–(f) As in (a)–(c), but for dewpoint temperature.
99th percentiles alone exhibit a super C-C scaling transition, consistent with previous studies (Hardwick Jones et al. 2010; Westra et al. 2014; see also Table 1).

The same analyses of precipitation scaling were performed again but now using dewpoint temperatures (Figs. 2d–f), which is an absolute humidity measure (Lenderink et al. 2011). Here a 4°–25°C range of dewpoint temperature was used, which covers most of the station data (not shown). Overall, the precipitation dependence on dewpoint temperature was found to be very similar to that on temperature. The dependency becomes stronger as the time scales get shorter and the percentiles of precipitation become higher. Hourly precipitation extremes follow a C-C rate below 18°C of dewpoint temperature and the rate rises to a doubled C-C rate above 18°C. For dewpoint temperature above 22°C, hourly precipitation extremes show no dependency on dewpoint temperature, which in comparison with the temperature scaling (which decreases beyond a critical level) confirms that moisture is a limiting factor at high temperature in South Korea as in other regions (Lenderink et al. 2011; Panthou et al. 2014; also see below for humidity scaling results). It is also interesting to note that almost the same leveling off of extreme hourly precipitation occurs in the Hong Kong data above 23°C with similar intensity (e.g., for the 99th percentile it is approximately 30 mm h\(^{-1}\); Lenderink et al. 2011), suggesting an universality in dewpoint temperature scaling across different regions.

Figure 3 shows distributions of the scaling slope of hourly precipitation and the peak temperatures obtained from each station for 99th, 90th, and 75th percentiles. Extreme precipitation was more sensitive to increases in temperature for all stations, with some regional differences in magnitude. The scaling of extreme precipitation in South Korea was 7%–11% °C\(^{-1}\) except for three stations located on the east coast. It should be noted that the scaling here is based on the whole temperature range up to the peak temperature, including the scaling transition around 20°C, which occurs at many stations (not shown). The topography such as high altitudes and mountain ranges presumably had an influence on scaling at the eastern coast stations, possibly through mountain-wave dynamics (cf. Jang and Chun 2010; Shi and Durran 2016), details of which need further investigation. Also, there is a slight horizontal gradient of the scaling slope across stations, larger in the western region than in the east (Fig. 3a). A similar horizontal scaling gradient has also been found in North America (Mishra et al. 2012), and the surrounding environment such as the distribution of oceans and landmasses seems to affect the scaling pattern (Panthou et al. 2014; Lepore et al. 2015). The scaling slopes observed at stations get weaker for lower percentiles (Figs. 3b,c), consistent with South Korean results from aggregated data in Fig. 2, confirming that less-extreme precipitation is less sensitive to temperature change. In contrast to the difference in scaling slope between the percentiles, all stations experience maximum precipitation around 24°C regardless of the percentile (Figs. 3d–f). Therefore, external forcings such as synoptic dynamics or changes in humidity likely have an influence at high temperatures (Hardwick Jones et al. 2010; Utsumi et al. 2011; Chan et al. 2016; Loriaux et al. 2017). In this regard, humidity change with temperature is analyzed below.

To exceed moisture constraints in the scaling of extreme precipitation, the role of convective activity is important (Loriaux et al. 2013; Berg et al. 2013). Figure 4 presents the frequency distributions of stratiform and convective rain events in comparison with all events. The frequency of all precipitation events in South Korea displays a peaklike pattern, in which precipitation events are concentrated roughly at temperatures of 22°–24°C in the boreal summer owing to the influence of the East Asia summer monsoon (J.-Y. Lee et al. 2017). Overall, stratiform or large-scale precipitation is prevalent over the whole temperature range with a relatively small fraction of convective precipitation, but the frequency of convective precipitation increases with a rise in temperature (Berg and Haerter 2013). In particular, the fraction of convective extreme precipitation increases rapidly around 20°C, which coincides with the temperature of scaling transition from the C-C to super C-C rate (Fig. 2). This suggests that the transition of scaling rate may be partly due to the statistical effect (Haerter and Berg 2009; Berg and Haerter 2013). In European regions, large-scale precipitation is similarly dominant at low temperatures, but convective precipitation is more pronounced at higher temperatures, having a frequency similar to that of stratiform one (Berg and Haerter 2013). However, in South Korea the frequency of stratiform precipitation is generally much higher (10 times larger in total precipitation and double in extreme precipitation) than that of convective precipitation (Fig. 4, top). The dominance of stratiform events in South Korea is consistent with recent studies of satellite data, showing that stratiform events are much more frequent than convective events over the northern part of East Asia (Fu and Liu 2003; Lu et al. 2016). This prevalence of stratiform precipitation seems to be partly due to the dominant influence of East Asian summer monsoon, which accompanies a large-scale atmospheric circulation system, transporting water vapor into the northern land and favoring stratiform precipitation (e.g., Fu et al. 2016; Lu et al. 2016). Accordingly, for extreme precipitation, the proportion of convective precipitation
reaches about half of total precipitation at high temperatures beyond 24°C (Fig. 4), whereas the same fraction occurs at lower temperatures (about 15°C) in Europe. This suggests that the discrepancy in the climatological frequency distributions of precipitation types may lead to a difference in transition temperatures between South Korea and Europe.

To further examine the scaling characteristics of the precipitation types, we analyzed the precipitation–temperature relationships for convective and stratiform rainfall events separately, and compared results with those from all events (Fig. 5a). The intensity of precipitation extremes (99th percentiles) of both types increases with a rise in temperature. While no significant
The exceedance of the C-C rate occurs for stratiform precipitation, convective precipitation exceeds the C-C rate above 12°C. The scaling of total precipitation is similar to that of stratiform precipitation at temperatures below 20°C but it becomes similar to the scaling of convective precipitation at temperatures higher than 20°C, which resembles the increase in frequencies of the convective events in Fig. 4. In addition, only extreme events (>99th percentile) of stratiform precipitation change with the C-C rate, but convective rainfall exceeds the C-C rate for about the 55th percentile and higher (Fig. 5b). This means that convective rainfall is basically more sensitive to changes in temperature and thereby contributes importantly to the characteristics of scaling, which supports the physical argument (Berg et al. 2013; Moseley et al. 2013).

Overall, the patterns of temperature and extreme precipitation scaling for South Korea are similar to those for Germany (Berg et al. 2013), including the C-C rate of the total and stratiform precipitation, the super C-C rate of convective precipitation, and the relation of super C-C transition temperature to the fraction of convective events. In particular, the fraction of convective precipitation when the scaling transition occurs from the C-C to super C-C rate is quite similar, about 0.2, between the two countries (Berg et al. 2013). This supports the idea that the role of convective events is
critical in determining the scaling, and that the relatively small proportion of convective precipitation in South Korea may be a cause of the higher temperature of scaling transition to super C-C scaling than in Europe. On the other hand, peak temperature appears around 23°C–24°C for both precipitation types (Fig. 5a), which was found to be identical across regions as summarized in Table 1. It is interesting to see that peak temperatures are also stable across percentiles (Fig. 5c), indicating the robust influence of moisture limitation (see below).

As seen above, precipitation scaling levels off or declines above a threshold temperature at around 24°C for all time scales, percentiles, and precipitation types (Figs. 2 and 5). To further check whether moisture limitation is indeed related to this reduced scaling at high temperature, we investigated changes in the relative humidity (RH) and specific humidity (SH) with temperature for the extreme hourly precipitation based on the 99th percentile (Hardwick Jones et al. 2010). Figure 6 shows results in comparison with those for total precipitation and dry conditions. When precipitation occurs, RH remains near constant at low temperatures in accordance with the C-C relation, although there is some fluctuation in the range of 85%–90%. The fluctuation in RH is larger during convective rainfall, perhaps owing to its shorter duration and relatively smaller sample size (Fig. 4). However, RH tends to decrease significantly for both extremes and total precipitation at temperature beyond 24°C, which is consistent with previous findings found in other regions (Hardwick Jones et al. 2010; Panthou et al. 2014; Westra et al. 2014; see Table 1). A similar pattern appears in SH. SH increases exponentially following the C-C rate with increases in temperature until the peak temperature is reached (Fig. 6). However, above the peak temperature, the increase in SH cannot keep up with the increase in the moisture availability and finally levels off. This means that the C-C relation does not hold any longer at higher temperatures and that other mechanisms with suppressing moisture transport possibly affect the scaling. Changes in the precipitation environment caused by a lack of moisture can lead to a decline in scaling at high temperatures. In this respect, the physical role of the synoptic situation might be also important, because anomalous high pressure systems can affect scaling by suppressing convection and blocking the inflow of supplies of moisture (Chan et al. 2016). As a whole, these results support that moisture is an important limiting factor to precipitation scaling, driving a peaklike pattern, which is well consistent with results obtained from using dewpoint temperature as a scale variable (Figs. 2d–f).

4. Summary and conclusions

This study examined the relationship between sub-daily precipitation and temperature using data from 26 stations over South Korea during the period 1980–2014. Mechanisms responsible for the scaling pattern were explored by analyzing its dependence on precipitation types, estimated from cloud observations. In particular, the role of convective precipitation in shaping the scaling was investigated considering its change in frequency and fraction to the total precipitation events with temperature. Results show that generally short time scales and more extreme precipitation were more sensitive to temperature changes, as reported in previous studies. In
particular, changes in extreme hourly precipitation displayed a scaling transition around 20°C from the C-C rate at low temperatures to the super C-C scaling at high temperatures. Convective precipitation was found to play a key role in the scaling transition in South Korea in two ways.

First, the fraction of the convective rainfall increases rapidly with temperature, contributing more to the total precipitation scaling as temperature rises, which seems to induce a scaling transition. This scaling transition and the contribution of the convective precipitation found in South Korea is generally similar to those reported in other regions, with the transition starting when the fraction of convective events becomes near 0.2. However, the transition temperature is much higher (20°C) in South Korea than in Europe (12°C), which is likely due to the generally lower frequency of the convective precipitation in South Korea. Second, convective extreme precipitation is found to respond more sensitively to temperature change, following a doubled C-C scaling at temperatures above 12°C, while the scaling slope for stratiform extreme precipitation follows the C-C rate.

The basic hypothesis of the C-C relation is that as the temperature increases relative humidity remains constant and specific humidity increases following the increase in moisture availability in the atmosphere. In contrast to this constraint, precipitation dependence on temperature in South Korea displays a peaklike pattern, with a positive relation until 24°C and then a negative relation above 24°C. This pattern appears robustly for all time scales and all percentiles of precipitations, consistent with results from other midlatitude regions. Considerable change in humidity is found to affect the precipitation scaling such that above 24°C relative humidity decreases significantly and specific humidity levels off. Scaling results based on extreme precipitation—depoint temperature relationship also exhibits a leveling off above 22°C, which in comparison with temperature scaling confirms the dominant role of moisture limitation at high temperature in this region.

Our results support that both statistical and physical mechanisms (Haerter and Berg 2009; Berg et al. 2013; Westra et al. 2014), suggested based on European data, are at work over East Asia and in particular confirm the important role of fraction of convective events in determining patterns of the scaling transition. Also, it is reaffirmed that humidity decrease provides a limiting factor to the precipitation intensification at high temperatures (Hardwick Jones et al. 2010; Lenderink et al. 2011; Panthou et al. 2014). Further investigation should be carried out to identify mechanism details for changing characteristics of convective events with temperature, considering convection duration, dynamic feedback, and associated synoptic conditions (Westra et al. 2014). In this regard, recent observational and modeling studies suggested possible importance of convective updrafts (Singleton and Toumi 2013; Moseley et al. 2016; Loriaux et al. 2017). Understanding the properties and mechanisms of changes in convective cells among different regions in terms of temperature scaling is fundamental for future prediction of extreme precipitation under global warming (Ban et al. 2014; Westra et al. 2014; Zhang et al. 2017).

Acknowledgments. The authors thank three anonymous reviewers for their constructive comments. This work was supported by the Korea Meteorological Administration Research and Development Program under Grant KMIPA 2016-6040 and by the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2017R1A2B008951).

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