Does higher surface temperature intensify extreme precipitation?

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[1] Recently, against the backdrop of current climate, several regional studies have investigated the applicability of the Clausius–Clapeyron relation to the scaling relationship between extreme precipitation intensity and surface air temperature. Nevertheless, the temperature relationship of the extreme precipitation intensity on a global scale is still unclear. We assess, for the first time, the global relationship between the extreme daily precipitation intensity and the daily surface air temperature using in-situ data. The extreme daily precipitation intensity increased monotonically with the daily surface air temperature at high latitudes and decreased monotonically in the tropics. Similarly, the extreme daily precipitation intensity at middle latitudes increased at low temperatures and decreased at high temperatures; this decrease could be largely attributed to the decrease in the wet-event duration. The Clausius–Clapeyron scaling is applicable to the increase in the extreme daily precipitation intensity in a limited number of regions. However, the potential applicability of the Clausius–Clapeyron scaling on sub-hourly timescale was observed, even in regions where the Clausius–Clapeyron scaling on daily timescale was not applicable. This implies the potential of warming to intensify extreme precipitation on sub-hourly timescales. **Citation:** Utsumi, N., S. Seto, S. Kanae, E. E. Maeda, and T. Oki (2011), Does higher surface temperature intensify extreme precipitation?, *Geophys. Res. Lett.*, *38*, L16708, doi:10.1029/2011GL048426.

1. Introduction

[2] Intensification of extreme hydrometeorological events by natural and anthropogenically forced climate change is of great concern for the society [*Oki and Kanae*, 2006; *Pall et al.*, 2011; *Min et al.*, 2011]. Precipitation intensity is projected to increase in most regions under warmer climates, and the increase in precipitation extremes will be larger than that in the mean precipitation [*Meehl et al.*, 2007]. The increase in the atmospheric water-holding capacity associated with a temperature increase (described by the Clausius–Clapeyron (CC) relation) considerably influences the changes in the extreme precipitation intensity under warmer climates [*Trenberth et al.*, 2003]. Studies based on numerical models have revealed that the rate of increase in the extreme daily precipitation associated with atmospheric warming is consistent with that of the CC relation (~7%/°C) [*Allen and Ingram*, 2002; *Pall et al.*, 2007; *Kharin et al.*, 2007]. However, deviation from the CC scaling is feasible given the changes in the atmospheric dynamics [*O'Gorman and Schneider*, 2009; *Sugiyama et al.*, 2010]. Hence, the applicability of the CC scaling is still undetermined.

[3] Recently, a study based on in-situ data found that in De Bilt, the Netherlands, the extreme daily precipitation intensity increased along with the daily surface air temperature (T_a) at a rate similar to the CC rate (7%/°C) in the T_a range below 8–10°C and at a sub-CC rate at high temperatures [*Lenderink and van Meijgaard*, 2008]. A similar increase in the extreme daily precipitation intensity was found on the hourly timescale, except that the rate of increase in the intensity at high temperatures was larger than the CC rate (the so-called "super-CC rate"). A change in the relative contributions of large-scale and convective precipitation was proposed by studies in Germany as a possible cause for this super-CC rate [*Haerter and Berg*, 2009; *Berg and Haerter*, 2011]. Following the framework of the study conducted in De Bilt, a study based on a gridded 0.44°-resolution observational dataset covering all of Europe revealed that the extreme daily precipitation intensity increases with T_a in winter (this increase is limited by the CC relation) and that the intensity decreases with an increase in T_a in summer [*Berg et al.*, 2009]. In Australia, the extreme daily precipitation intensity from in-situ data was found to increase with T_a to 20–26°C and decrease at higher temperatures [*Hardwick Jones et al.*, 2010]. The rate of increase in the extreme daily precipitation intensity was not necessarily consistent with the CC rate. The CC like rate was found only for timescales shorter than 30-min.

[4] However, the temperature relationship of the extreme daily precipitation intensity across the world is still unclear. Therefore, this study addresses the following questions based on a global observational dataset: In what regions and for which temperature ranges are the increases or decreases in the extreme daily precipitation intensity with increases in T_a observed? If the increases in the extreme daily precipitation intensity are observed, to what extent is the CC scaling applicable? Further, when decreases in the extreme daily precipitation intensity are observed, what are the causes of the decreases: the decreases in the precipitation-event intensity and/or duration?

[5] We note that the CC rate is a function of temperature (e.g., ~7.3%/°C at 0°C, ~6.2%/°C at 20°C) and hence of latitude. For simplicity, 7%/°C is used as a representative value for the CC rate in this study. We also note that the surface air temperature could be affected by extreme precipitation, although the surface air temperature was assumed to be a proxy for the extreme precipitation intensity in this study.

2. Relation Between Extreme Daily Precipitation Intensity and Daily Surface Temperature Across the World

[6] We analyzed global in-situ daily precipitation and T_a data obtained from the Global Historical Climatology

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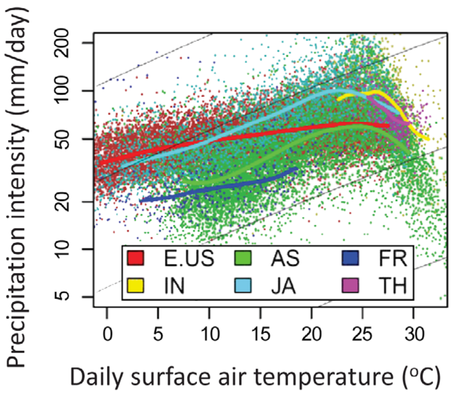

Figure 1. Behavior of P_{99_d} in six countries (Eastern United States (E.US), Australia (AS), France (FR), India (IN), Japan (JA), Thailand (TH)). "E.US" is the part of the United States extending from 22°N to 50°N and 65°W to 85°W. Each plot shows P_{99_d} for each T_a bin at each station. Thick lines denote the LOWESS smoothed lines for the six countries. CC scaling is illustrated by thin black lines for reference.

Network–Daily (GHCN-Daily) (available at http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). GHCN-Daily contains over 43,000 stations. Most of these stations report precipitation values, and more than 23,000 stations report daily maximum and minimum temperatures. Some stations have records spanning over 100 years. To improve the heterogeneity of the spatial density of stations, we selected observational stations containing the longest time series data in each 0.5° × 0.5° longitude-latitude grid box, resulting in a subset of approximately 8,900 stations considered in this study. The 99th-percentile daily precipitation intensity (P_{99_d}) was estimated as a function of T_a for each station following the framework of the earlier studies [e.g., *Lenderink and van Meijgaard*, 2008; *Hardwick Jones et al.*, 2010; *Berg and Haerter*, 2011] using only the data for wet days. Because GHCN-Daily provides only daily maximum and minimum surface air temperatures, the average of daily maximum and minimum surface air temperature was used as the approximate mean daily surface air temperature, T_a. The precipitation data from each station were first stratified by T_a, and then, for each temperature bin with a variable width, P_{99_d} was calculated. The average temperature bin size was defined as 2°C but was adjusted so that each bin had roughly the same number of data values. We required at least 150 data values in each bin. The average temperature for each bin was used in the analysis. This procedure makes the result more robust than an analysis with even-width bins because the effect of the difference in the number of observations in each bin can be neglected. Then, for a stronger signal and more robust analysis, combinations of P_{99_d} and T_a in each non-overlapping 4° × 4° grid box were gathered and analyses were carried out for each 4° × 4° grid box. We verified that the fundamental conclusion did not change even when the analysis was carried out for each station.

[7] For most regions, changes in P_{99_d} with T_a could be classified into three categories as observed previously [*Berg et al.*, 2009; *Hardwick Jones et al.*, 2010]: a monotonic increase in P_{99_d} with an increase in T_a (e.g., France (Figure 1)), a monotonic decrease (e.g., Thailand (Figure 1)), and a peak-like structure (e.g., Eastern United States, Australia, India, and Japan (Figure 1)) where P_{99_d} increased with T_a up to a threshold T_a (hereafter called "peak-point temperature") and then decreased with a further increase in T_a. The peak-point temperature was detected by applying "locally weighted regression (LOWESS) smoothing" [*Cleveland*, 1979] to the P_{99_d} scatter plots on T_a. The temperature at which the LOWESS smoothed curve had a peak was regarded as the peak-point temperature. We verified that the LOWESS smoothing captured the peak-point temperature well. The monotonic increase in P_{99_d} was dominant at very high latitudes (>55°N) (Figure 2a). The monotonic decrease was dominant in the tropics (20°N–20°S), which is consistent with the result found by a regional study in Australia [*Hardwick Jones et al.*, 2010]. Mid-latitudes (20°–55°N and S) exhibited a peak-like structure of P_{99_d}. *Berg et al.* [2009] reported the decrease in the extreme daily precipitation intensity with an increase in T_a in summer in Europe. In our result without the separation of seasons, such negative scaling disappeared at high latitudes in Europe. Among the regions with peak-like structures, high-latitude regions or mountainous regions (e.g., the Rocky Mountains) tend to have low peak-point temperatures (Figure 2a), implying that the peak-point temperature is closely related to the local temperature (see auxiliary material).[1]

[8] To address the second question, "If an increase is observed in P_{99_d}, to what extent is the CC scaling applicable to it?", we investigated the applicability of the CC scaling to the increasing phase in P_{99_d} using an exponential regression that related precipitation, P, to temperature changes, ΔT, following the methodology proposed by *Hardwick Jones et al.* [2010]:

$$P_2 = P_1(1+\alpha)^{\Delta T},$$

where α is the rate at which P changes with T_a. Exponential regression fitting was then applied to the gathered data in each 4° × 4° grid box. If a peak-like structure was observed in the relationship between P_{99_d} and T_a, regression fitting was applied only up to the peak-point temperature.

[9] A limited number of regions had α similar to the CC rate of 7%/°C (green color in Figure 2b). The CC-like relation was dominant in mid-latitudes (30°N–45°N) of East Asia, pacific coastal regions of North America, Eastern Australia, and Eastern Europe. α larger than the CC rate was observed mainly in the region 15°–30°N and S except in North America. The tropics commonly exhibited negative α values. α in other regions was mostly smaller than the CC rate.

3. Analysis Using Fine Temporal-Resolution Data in Japan

[10] Because in many regions, we observed decreases in P_{99_d} when T_a increased, we analyzed sub-hourly temporal resolution data to address the third question ("what are the causes of the decreases in P_{99_d}: the decreases in the precipitation-event intensity and/or duration?"). Fine temporal-resolution in-situ data are not readily available on the global scale. In this study, we set the study area to Japan because sub-hourly in-situ data that cover a wide range of

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048426.

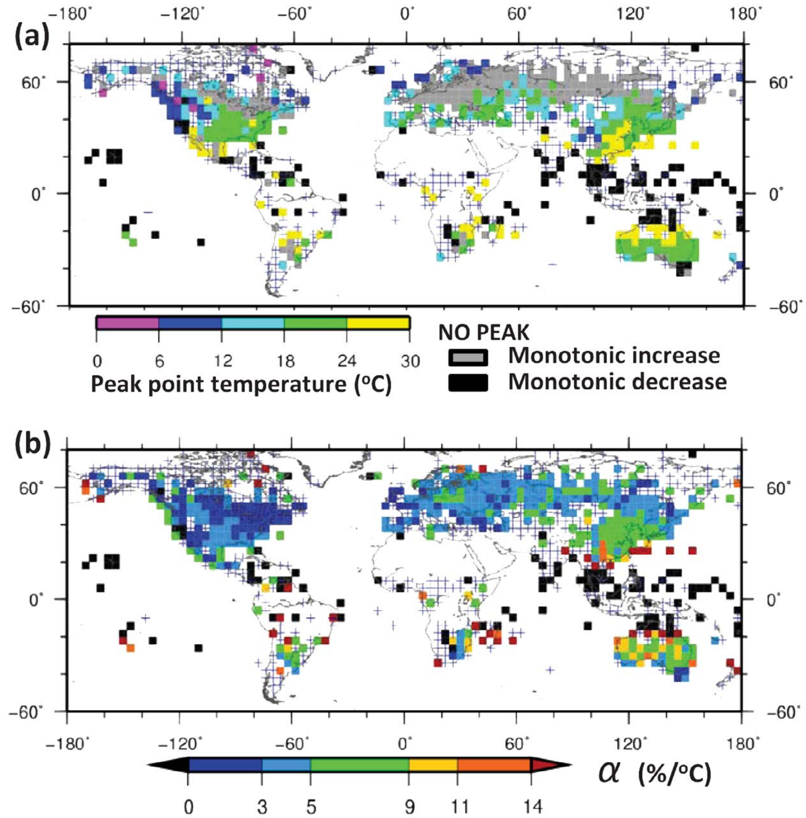

Figure 2. Global distribution of (a) peak-point temperatures and (b) α for P_{99_d}. The colored grid boxes have α with 5% significance level. Grid boxes with no significance are indicated by crosses. White color indicates grids with no data suitable for the analysis.

climatological regimes are available for Japan. We analyzed hourly and 10-min meteorological data for 17 stations located across three Japanese regions (North Island, Kyushu, and Southern Islands) obtained from the Automated Meteorological Data Acquisition System (AMeDAS), maintained by Japan Meteorological Agency. We considered the period 1980–2004 for hourly data and 1995–2004 for 10-min data. The 99th-percentile precipitations for the 10-min, hourly, 6-hourly, and daily timescales (P_{99_10m}, P_{99_1h}, P_{99_6h}, and P_{99_d}, respectively) were estimated based on 10-min (for P_{99_10m}) and hourly data (for P_{99_h}, P_{99_6h}, and P_{99_d}) as a function of T_a. "Heavy precipitation days" were defined as conditioned days having daily precipitation amounts that exceeded the 90th-percentile daily precipitation and for which two statistics, "Wet time fraction" (*WTF*) and "Mean instantaneous precipitation intensity" (P_{inst}), were computed. The 90th percentile, not the 99th percentile, was used as the threshold to ensure an adequate sample size. We obtained similar analysis results for both percentile thresholds but with noise for the case of the 99th-percentile threshold. *WTF* was defined as the mean time fraction of wet events on "heavy precipitation days." P_{inst} was defined as

$$P_{inst} = P_{day}/D_{wet},$$

where P_{day} is the total precipitation on "heavy precipitation days" and D_{wet} is the total time (min) of wet events on "heavy precipitation days." P_{inst} represents the mean precipitation intensity considering only wet events on "heavy precipitation days." *WTF* and P_{inst} were computed from the 10-min data.

[11] P_{99_d} shows a monotonic increase with T_a for the North Island and a clear peak-like structure for Kyushu and the Southern Islands (Figure 3), which represents the latitudinal behavior of P_{99_d} with an increase in T_a found in the global analysis: a monotonic increase in P_{99_d} at high latitudes and a peak-like structure at mid-latitudes (Figure 2a). The decreases in P_{99_d} at high temperatures in Kyushu and the Southern Islands were accompanied by steep decreases in *WTF*. In contrast to *WTF*, P_{inst} did not decrease at high temperatures in all regions even when P_{99_d} and *WTF* decreased with increases in T_a. Hence, the decreases in P_{99_d} could be largely attributed to the decreases in *WTF*, not to the decreases in the intensity of individual storms. If the considered timescale became shorter and reached 10-min, the clear peak like structure was not observed any more (Figure 3). The decreases in *WTF* found here were in line with the tendency that the wet-event duration decreases with an increase in temperature in Europe, as shown by *Haerter et al.* [2010], except that decreases in *WTF* were found only at high temperatures in this study. Our result explicitly attributes the decreases in the extreme precipitation intensity at high temperatures, reported by previous regional studies [e.g., *Berg et al.*, 2009; *Hardwick Jones et al.*, 2010], to the changes in the wet-event duration measured by *WTF*. *Hardwick Jones et al.* [2010] observed in Australia that the decrease in the extreme daily precipitation intensity at high temperatures is accompanied by a decrease in the relative

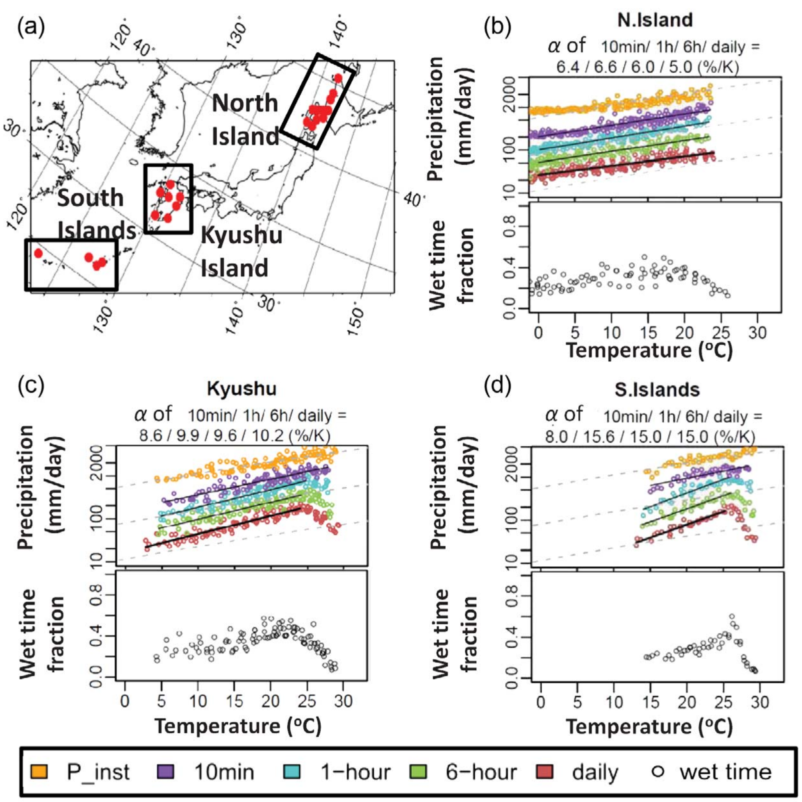

Figure 3. (a) Locations of three regions analyzed. Red circles in the map indicate the stations included for the analysis. (b, c, and d) The behaviors of P_{99_10m}, P_{99_1h}, P_{99_6h}, P_{99_d}, P_{inst}, and *WTF* are shown. The units of precipitations are converted to mm/day, and P_{inst} is multiplied by 10 for visibility. The values of α for P_{99_10m}, P_{99_1h}, P_{99_6h}, and P_{99_d} estimated by exponential fitting are shown above each graph (Figures 3b–3d).

humidity. The saturation level of the atmosphere would affect the precipitation trigger [*Berg et al.*, 2009], which partly determines the *WTF*. Hence, the saturation level of the atmosphere could be related to the decreases in *WTF* and hence in the extreme precipitation intensity. However, it should be noted that the atmospheric saturation level can be both a cause and a consequence of the extreme precipitation.

[12] *Lenderink et al.* [2011] observed a peak like structure for hourly precipitation extremes in the subtropics (Hong Kong), while such a peak like structure was not observed in a higher latitude (the Netherlands). Our results confirm similar latitudinal difference for hourly and 6-hourly precipitation in Japan (Figure 3). Furthermore, such latitudinal difference can be seen across the world at least on the daily timescale (Figure 2). *Berg and Haerter* [2011] found in Germany that the 5-min and hourly convective extreme precipitation level off at high temperatures instead of increasing with temperature. They proposed an expectation that if the data at higher temperatures (>20°C) is available, total extreme precipitation intensity (without separation of large-scale and convective precipitation) would level off because the convective precipitation would become dominant. Our result in Kyushu and the South Islands, which covers higher temperatures than that of *Berg and Haerter* [2011], provides supportive fact for their expectation on timescales longer than 1-hour, although the precipitation intensity of our result does decrease (not level off). The clear leveling off of the precipitation extremes was not observed on the 10-min timescale in contrast to the result of *Berg and Haerter* [2011].

[13] On the short timescales, α tends to be close to the CC rate of 7%/°C (Figure 3). This finding can be supported by the fact that the latitudinal gradient of the historical extreme 10-min precipitation in Japan better agrees with the latitudinal gradient of the mean precipitable water than that of the long timescale extreme precipitations [*Ninomiya*, 1977]. A similar timescale tendency of the applicability of the CC scaling was observed in Australia [*Hardwick Jones et al.*, 2010] and our result was not consistent with the result obtained for Germany by *Haerter et al.* [2010], who argued that the CC scaling may not provide an accurate estimate of the temperature relationship of precipitation at any temporal resolution. Further studies are needed to assess the applicability of the CC scaling on sub-hourly timescales.

4. Conclusions

[14] The global relationship between the extreme daily precipitation intensity and surface air temperature was investigated using a global in-situ dataset. The monotonic increase in P_{99_d} with T_d was observed almost only at high latitudes (>55°N). At mid-latitudes (20°–55°N and S), the relationship between P_{99_d} and T_d exhibited a peak-like structure. In the tropics (20°S–20°N), P_{99_d} exhibited a monotonic decrease with an increase in T_d. Even for the

regions where the increase in P_{99_d} with T_d was observed, the number of regions where the CC scaling is applicable for the increase in P_{99_d} with T_d was limited.

[15] The analysis using sub-hourly timescale data in Japan revealed that the decrease in the extreme daily precipitation intensity at high temperatures was well explained by the decrease in the duration of the precipitation events, not by the decrease in the precipitation intensity of individual storms. Furthermore, the extreme precipitation intensity on the 10-min timescale did not decrease even at high temperatures where the extreme precipitation intensity on the daily timescale decreased. When the timescale was changed from daily to 10-min, the rate of increase in the extreme precipitation intensity came closer to the CC rate. Further studies are necessary to investigate whether the extreme precipitation on short timescales in other regions, especially in the regions where the CC scaling on daily timescale was not applicable, shows α similar to the CC rate. If so, as revealed in the case of the low latitudes in Japan, the temperature increase will increase the potential of severe extreme precipitation scaled by the rate similar to the CC rate on short timescales, which would cause flash floods in cities and small catchments. We note that the results of this study were derived from the current climate. Whether the temperature relationship of the extreme precipitation intensity changes with a global climate change is a topic for future study.

[16] The findings of this study contribute to the assessment of the ability of climate models to represent the characteristics of extreme precipitation. An appropriate representation of the atmospheric moisture content should be integral to the simulation of extreme precipitation on short timescales such as 10-min. In contrast, an appropriate representation of the wet-event duration is required when considering long timescales. Such an assessment would improve the reliability of the extreme precipitation simulations provided by the current models and allow more realistic representations of future meteorological events in warmer climates.

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