Unexpected rise in extreme precipitation caused by a shift in rain type?

To the Editor — In their letter (*Nature Geosci.* **1,** 511–514; 2008), Geert Lenderink and Erik van Meijgaard study an hourly time series of precipitation data obtained at De Bilt, The Netherlands. They observed an exponential increase of heavy precipitation with temperature, with a coefficient close to that of the Clausius–Clapeyron relation for lower temperatures, whereas for higher temperatures they found super-Clausius–Clapeyron behaviour. We argue that the super-Clausius–Clapeyron scaling for hourly, but not for daily, precipitation arises because of the superposition of two facts: (1) the dramatically different timescales between large-scale and convective precipitation and (2) the dominance of convective precipitation for high temperatures and the dominance of large-scale precipitation for cool temperatures. Our theory also explains the unusual transition between Clausius–Clapeyron and super-Clausius–Clapeyron scaling for hourly precipitation as the temperature changes.

It is of fundamental interest to understand the origin of the changes in precipitation extremes reported by Lenderink and van Meijgaard, considering, for example, flood risk. To this end we consider the wet-day probability density function of total daily precipitation (P_{tot}), which depends on precipitation intensity and temperature. This is the sum of the probability density functions of convective precipitation (P_c) and large-scale precipitation (P_{ls}). By convective precipitation we mean showery rain that falls over a certain area for a relatively short time, for example, during mid-latitude thunderstorm events in summer. Large-scale precipitation occurs, for example, due to slow ascent of air in synoptic systems.

Now we consider a given temperature range (T, $T + \Delta T$) and refer to the total amount of precipitation within this range as its weighting. Generally, higher intensities are less likely than lower intensities for both large-scale and convective precipitation events. Daily precipitation is accumulated over 24 h, and its intensity is therefore an average over this time interval.

When the transition is made to sub-daily temporal resolution (such as hourly in Lenderink and van Meijgaard) the different nature of large-scale and convective precipitation may emerge from the statistics. Whereas large-scale events take place at a lower rate during a larger part of the day, convective events are likely to occur as bursts of heavy rain during a smaller fraction of the day. The transition to sub-daily precipitation then leads to a more pronounced stretching of P_c towards higher intensities than is the case for P_{ls}. Note that the rescaling leaves the weighting of (T, $T + \Delta T$) unchanged. Hence, for P_{tot} different statistical behaviour and temperature dependence will emerge for daily, compared with sub-daily, resolution. In particular, any given percentile of large-scale and convective precipitation will shift by different offsets when the transition to sub-daily resolution is made. As large-scale (convective) precipitation dominates at low (high) temperatures, the corresponding percentile of total precipitation will follow that of large-scale (convective) precipitation there. In the intermediate temperature range an increase with an unexpected temperature dependence may occur (see Supplementary Information for mathematical details).

We illustrate our analysis in a simple example where the daily amount of

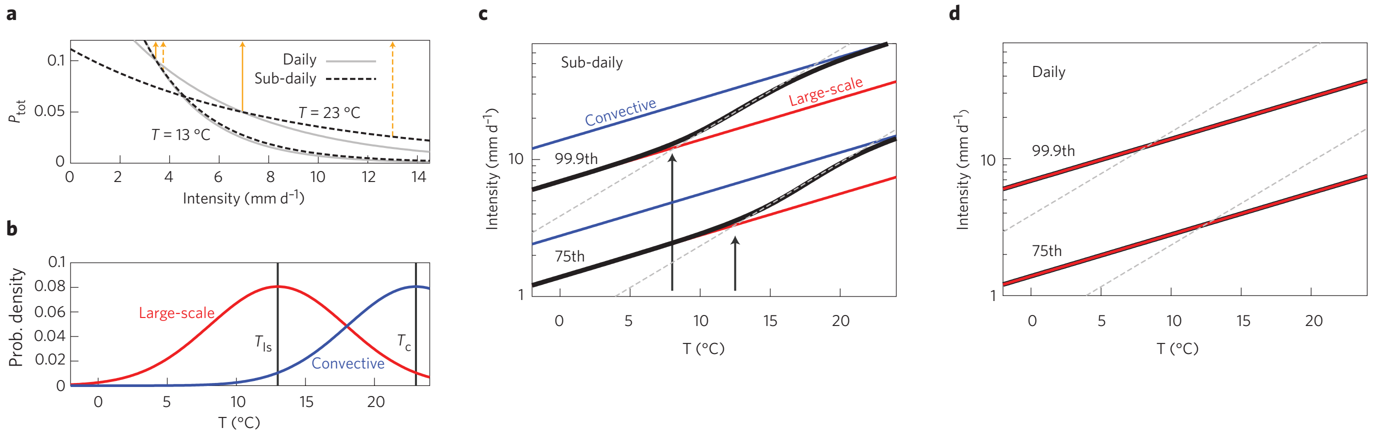

Figure 1 | Daily and sub-daily precipitation intensity distributions, weighting functions and precipitation percentiles. **a**, Probability density function of total precipitation at $T = 13$ °C and $T = 23$ °C. Solid lines are for daily values of total precipitation intensity, dashed lines are for sub-daily rescaling, orange arrows indicate 75th percentile. **b**, Weighting functions for large-scale (red) and convective (blue) precipitation as function of temperature: $T_{\mathrm{ls}} = 13$ °C and $T_c = 23$ °C are indicated by vertical lines. **c**, 99.9th (upper curves) and 75th (lower curves) sub-daily precipitation intensity percentile of large-scale (red), convective (blue) and total precipitation (black), and double Clausius–Clapeyron increase (dotted grey); arrows indicate onset of super-Clausius–Clapeyron behaviour. **d**, Same as **c** but for daily averaged precipitation intensity: all curves collapse on one, slope does not change as function of temperature. Note the logarithmic vertical scale in **c** and **d**.

convective (large-scale) precipitation occurs constantly during 12 (24) hours of the day. For the two weighting functions we chose equal Gaussian distributions centred at different temperatures $T_{ls} < T_c$ (Fig. 1b). We use identical daily distribution functions — $\rho(p, T) \equiv \exp(-p/\beta(T))$ where p is precipitation intensity, T is temperature and β is the scale parameter — with equal Clausius–Clapeyron-like exponential temperature dependence $\beta(T) = \exp(bT)$ where the coefficient of temperature dependence $b = 0.07\ \mathrm{K}^{-1}$. Hence, the only variations result from the difference between T_{ls} and T_c, and the transition to sub-daily statistics (as shown in Fig. 1a and b). The percentiles of the transformed P'_{ls}, P'_c and P'_{tot} are depicted in Fig. 1c. Whereas the distribution functions of the two types of precipitation have a Clausius–Clapeyron-like exponential increase of a given percentile intensity, the joint distribution may deviate from the Clausius–Clapeyron-like behaviour in the transition temperature region where the two weighting functions overlap. For the limit of low and high temperatures, Clausius–Clapeyron behaviour is approached. This feature can be observed in sub-daily data, whereas it disappears on a daily scale (compare Fig. 1c and d). This is precisely what Lenderink and van Meijgaard found, both in observational and model results (compare Fig. 1a and c in their paper). Additionally, their Fig. 1a shows a transition from Clausius–Clapeyron to super-Clausius–Clapeyron behaviour with an onset moving to lower temperatures for higher percentiles, which can also be seen in our Fig. 1c. We tested the analysis presented here on model data and found generally consistent results (see Supplementary Information).

In conclusion, we have provided a general argument which makes the origin of the unexpected increases in extremes obvious by simple histogram re-weighting for sub-daily values. Super-Clausius–Clapeyron behaviour emerges as a consequence of simultaneous Clausius–Clapeyron behaviour of both the large-scale and convective precipitation in the temperature regime where the two types coexist. Outside of this regime the Clausius–Clapeyron behaviour again emerges. Concerning precipitation in a changing climate, we suggest investigating whether seasons and regions with mainly large-scale or convective precipitation see only a Clausius–Clapeyron increase in extremes with temperature. For seasons and regions with coexistence of the two types, our analysis stresses the importance of studying whether the temperature of their transition shifts with changing climate.

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Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience.

J. O. Haerter[1]* and P. Berg[2]
[1]Max Planck Institute for Meteorology, 20146 Hamburg, Germany, [2]Institute for Meteorology and Climate Research, University of Karlsruhe and Forschungszentrum Karlsruhe, 76344 Karlsruhe, Germany.
*e-mail: jan.haerter@zmaw.de

Lenderink and van Meijgaard reply — In their correspondence, Haerter and Berg propose an interesting explanation of the super-Clausius–Clapeyron scaling of precipitation extremes we found in hourly observations at De Bilt, The Netherlands and reported in our letter (*Nature Geosci.* **1,** 511–514; 2008). They argue that because convective precipitation events are by their nature more intense than large-scale events, a change in relative frequency of occurrence of both precipitation types (histogram re-weighting) influences the scaling of precipitation extremes with temperature. They show that in an intermediate temperature range, linking the two precipitation regimes, the statistical effect of histogram re-weighting may give rise to a super-Clausius–Clapeyron scaling, even when the scaling of the large-scale and the convective events separately both satisfy the Clausius–Clapeyron relation.

For the most extreme precipitation events histogram re-weighting is only relevant when the number of convective events is relatively small compared with the number of large-scale events. For temperatures at which the number of convective events is larger than (or equal to) the number of large-scale events, the extreme 99.9th percentile is dominated by the scaling of the convective events (compare Fig. 1b and c in the correspondence from Haerter and Berg). The temperature range where the super-Clausius–Clapeyron relation is obtained is therefore primarily determined by the ratio between the number of convective and large-scale events as a function of temperature. This ratio follows from an arbitrary choice in the conceptual model of Haerter and Berg, not supported by observations and also considerably different from the climate model results (compare their Fig. 1b and Supplementary Fig. 1b).

We think that the manifestation of the super-Clausius–Clapeyron scaling has a physical origin, rather than the statistical origin proposed by Haerter and Berg; in our opinion it is a property of the convective regime itself, and results from the dynamics of convective clouds with stronger updrafts due to increased latent heat release as the temperature rises. The super-Clausius–Clapeyron scaling of sub-daily precipitation extremes is a robust feature in the observations at De Bilt. It is consistently obtained using different measures of the temperature (daily mean and daytime maximum), different time periods (all year, summer months, summer half-year), and different measures of the sub-daily precipitation intensity (mean daily intensity at wet hours, hourly intensity, and daily maximum of the hourly intensity). Considering the mean daily intensity at wet hours (daily sum divided by rainfall duration) as in Haerter and Berg, a dependency exceeding two times the Clausius-Clapeyron relation is found in the observations, without any clear sign of levelling off in the high temperature range (as would be expected from histogram re-weighting).

The atmospheric conditions may vary considerably across the range of temperatures for which the scaling has been obtained. This does not only determine the number of rainfall events (*Nature Geosci.* **1,** 511–514; 2008), whether precipitation is large-scale or convective (as mentioned in Haerter and Berg), but could also influence other aspects of shower complexes, such as their level of mesoscale organization or travel speed. These factors potentially affect the scaling relations found for the present-day climate and their interpretation in the context of climate change — although we think not in a crucial way — and need further investigation.

Geert Lenderink* and Erik van Meijgaard
Royal Netherlands Meteorological Institute (KNMI), 3730 AE De Bilt, PO Box 201, The Netherlands.
*e-mail: lenderin@knmi.nl