Increase in hourly precipitation extremes beyond expectations from temperature changes

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Changes in precipitation extremes under greenhouse warming are commonly assumed to be constrained by changes in the amounts of precipitable water in the atmosphere[1–4]. Global climate models generally predict only marginal changes in relative humidity[5], implying that the actual amount of atmospheric precipitable water scales with the water vapour content of saturation, which is governed by the Clausius–Clapeyron relation. Indeed, changes in daily precipitation extremes in global climate models seem to be consistent with the 7% increase per degree of warming given by the Clausius–Clapeyron relation[3,4], but it is uncertain how general this scaling behaviour is across timescales. Here, we analyse a 99-year record of hourly precipitation observations from De Bilt, the Netherlands, and find that one-hour precipitation extremes increase twice as fast with rising temperatures as expected from the Clausius–Clapeyron relation when daily mean temperatures exceed 12 °C. In addition, simulations with a high-resolution regional climate model show that one-hour precipitation extremes increase at a rate close to 14% per degree of warming in large parts of Europe. Our results demonstrate that changes in short-duration precipitation extremes may well exceed expectations from the Clausius–Clapeyron relation. These short-duration extreme events can have significant impacts, such as local flooding, erosion and water damage.

There is a general consensus that the character of precipitation—for instance, average, intensity and frequency—will change as climate changes[2,6,7]. However, predictions of future precipitation changes are also highly uncertain. Our understanding of the essential processes involved in precipitation formation—ranging from the large-scale atmospheric dynamics[8,9], meso-scale convective circulations[10], to the local precipitation microphysics at the smallest spatial and temporal scales[11]—is limited, as is our ability to model these processes in global and regional climate models.

The notion that the Clausius–Clapeyron relation may constrain future changes in extreme precipitation is based on the following arguments[1]. First, the atmospheric relative humidity remains relatively constant as climate changes, which causes the actual precipitable water to scale with the saturation value. Second, intense precipitation totals are mainly determined by the precipitable water already in the atmosphere. Third, the nature of the atmospheric circulation, with mainly the upward motions producing precipitation, does not change considerably. Whereas there is reasonable support that the first two assumptions are approximately valid at least at the larger scale[5,12,13], the third assumption is generally questioned[5,8,14]. Many global climate models (GCMs) predict changes in the large-scale atmospheric circulation and related changes in precipitation[8,9]. At the scale of convective showers, increased latent heat release may intensify the upward motions giving rise to a scaling exceeding the Clausius–Clapeyron relation, a super-Clausius–Clapeyron scaling[1]. Despite these reservations, the Clausius–Clapeyron relation is found to be a good predictor for changes in extreme daily precipitation in GCMs[2–4].

On a (sub-)daily timescale, the highest precipitation intensities are usually related to convective showers. Climate models do not explicitly resolve these showers, but use implicit parameterizations instead. Long-standing problems with these convective parameterizations exist, related to the onset and life cycle of the convective clouds[15]. Here, we investigate how modelled intensities compare with observations. Furthermore, the dependency of precipitation intensity on temperature found in the present-day climate is linked to the climate response in a long climate simulation with a regional climate model.

We start by analysing a 99-year record of quality controlled 1 h precipitation observations at De Bilt (52.10 °N, 5.18 °E) in the Netherlands. We present results for the 1 h precipitation intensity $I_{1\,\mathrm{h}}$, the daily maximum of the 1 h precipitation intensity $I_{1\,\mathrm{hmax}}$ and the daily intensity $I_{1\,\mathrm{d}}$, which is the 24 h precipitation sum. We stratified the precipitation data based on the daily mean temperature in bins of 2 °C width, and computed the 75th, 90th, 99th and 99.9th percentiles of the distribution of wet events (hours or days) in each bin.

Figure 1a,b shows different percentiles of the 1 h intensities $I_{1\,\mathrm{h}}$ and $I_{1\,\mathrm{hmax}}$ (on a logarithmic scale) in comparison with lines given by multiplications of the Clausius–Clapeyron relation. In general, $I_{1\,\mathrm{h}}$ and $I_{1\,\mathrm{hmax}}$ exhibit a similar scaling behaviour. For daily mean temperatures roughly below 12 °C, the 99th and 99.9th percentile of the 1 h intensities exhibit a temperature dependency close to the Clausius–Clapeyron relation. For higher temperatures, this dependency increases to two times the Clausius–Clapeyron relation. The lower, 75th and 90th, percentiles exhibit a less distinct scaling behaviour. In general, more extreme events (that is, the highest percentiles) show an earlier transition to the two-times Clausius–Clapeyron scaling than the less extreme events. Using the daily maximum temperature, instead of the mean temperature, a similar scaling behaviour is obtained (Supplementary Information, Fig. S1). Results for summer and winter periods separately reveal a

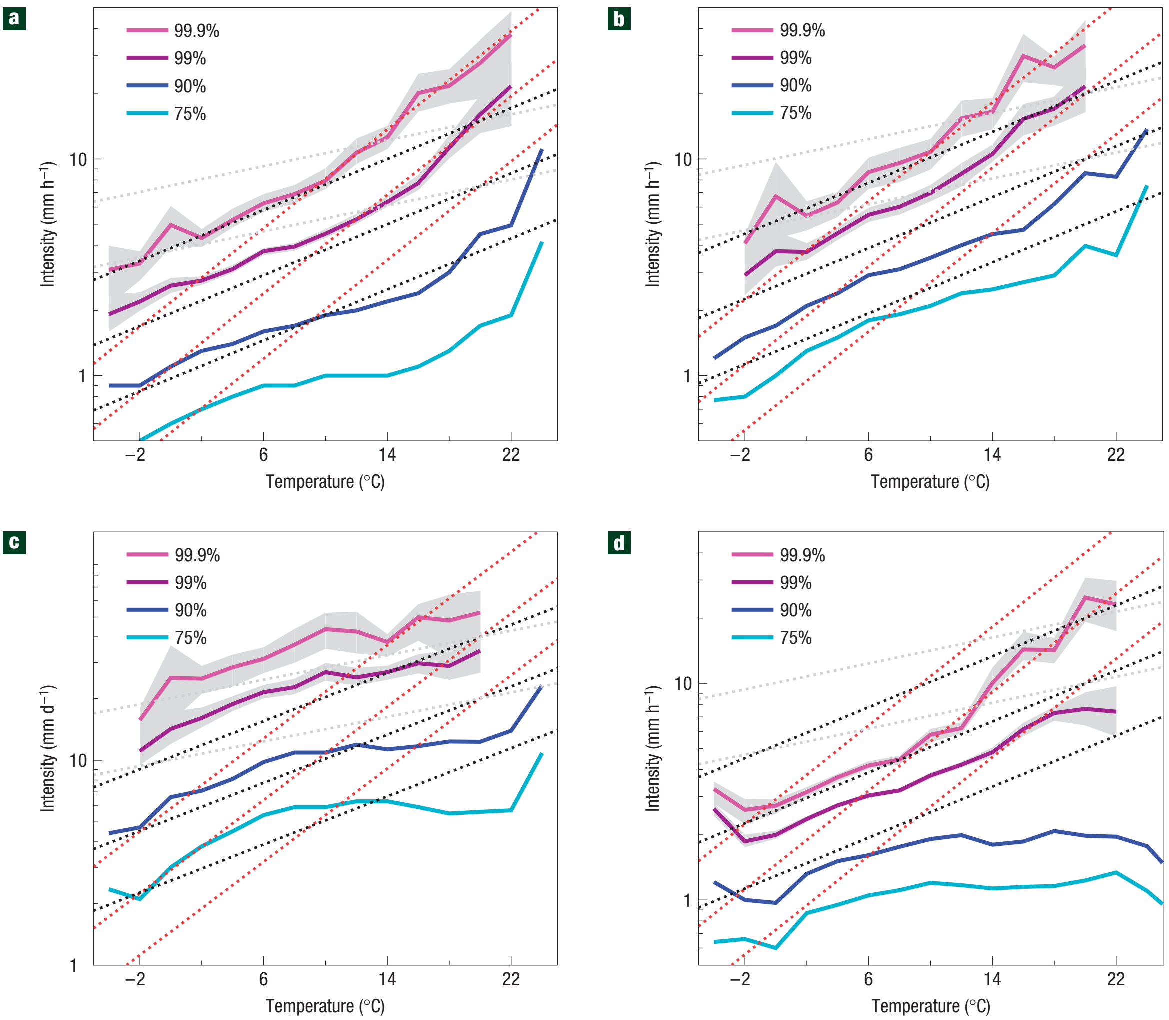

Figure 1 Percentiles of precipitation intensity on a logarithmic scale as a function of temperature. a, Observed 1 h precipitation intensity $I_{1\,h}$. **b**, Observed maximum 1 h precipitation intensity $I_{1\,hmax}$. **c**, Observed 1 d precipitation intensity $I_{1\,d}$. **d**, Modelled maximum 1 h precipitation intensity. Solid colour lines are the different percentiles. Grey bands, plotted only for the 99 and 99.9th percentile, are 90% confidence intervals estimated by the bootstrap. Dotted lines are the exponential relations given by 0.5 (light grey), 1 (black) and 2 (dark red) times the Clausius–Clapeyron relation.

super-Clausius–Clapeyron scaling for summer, and a scaling close to the Clausius–Clapeyron relation for winter. Winter precipitation is dominated by large-scale precipitation, which is governed by baroclinic instability. Summer precipitation is often of convective origin, for which latent heat release is the main source of energy of the upward motions. Compared with hourly intensities, the daily intensities $I_{1\,d}$ have a less well-defined scaling behaviour (Fig. 1c). For temperatures below 8–10 °C, approximately the Clausius–Clapeyron relation is found. For higher temperatures, except perhaps the uppermost temperature range, the scaling is sub-Clausius–Clapeyron.

To investigate whether or not these relations are reproduced by a state-of-the-art high-resolution climate model, we analysed a simulation of the present-day climate 1971–2000 from the regional climate model[16] RACMO2. The modelled 99.9th percentile of the hourly precipitation intensity scales similar to the observations: close to the Clausius–Clapeyron relation for temperatures below 12 °C and two times the Clausius–Clapeyron relation for temperatures above 12 °C (Fig. 1d). However, for temperatures above 20 °C and for the lower percentiles, the model fails to reproduce the observed steep intensification with temperature. The modelled intensities represent grid averages ($25 \times 25\,km^2$), whereas observations are point measurements, which could explain the discrepancy. However, model deficiencies[17] are likely to play a role as well. As in the observations, modelled daily intensities exhibit a less-well-defined scaling behaviour, with weaker temperature dependencies than the hourly intensity (Supplementary Information, Fig. S2).

Are these relations derived from day-to-day variability in present-day climate reflected in the response of extreme precipitation to climate change? We computed the relative change of summertime extreme precipitation between 1971–2000 and 2071–2100 in a climate integration with RACMO2. The data in individual grid points are pooled in small boxes of 5 × 4 degrees longitude–latitude to improve the signal-to-noise ratio. From this pooled data set, containing the data of about 300 individual grid points, the different percentiles of the distribution are computed. Unlike before, the percentiles are now computed using all hours and days, dry and wet, because it is the absolute frequency of occurrence of extremes that counts for society. Changes in intensity are scaled

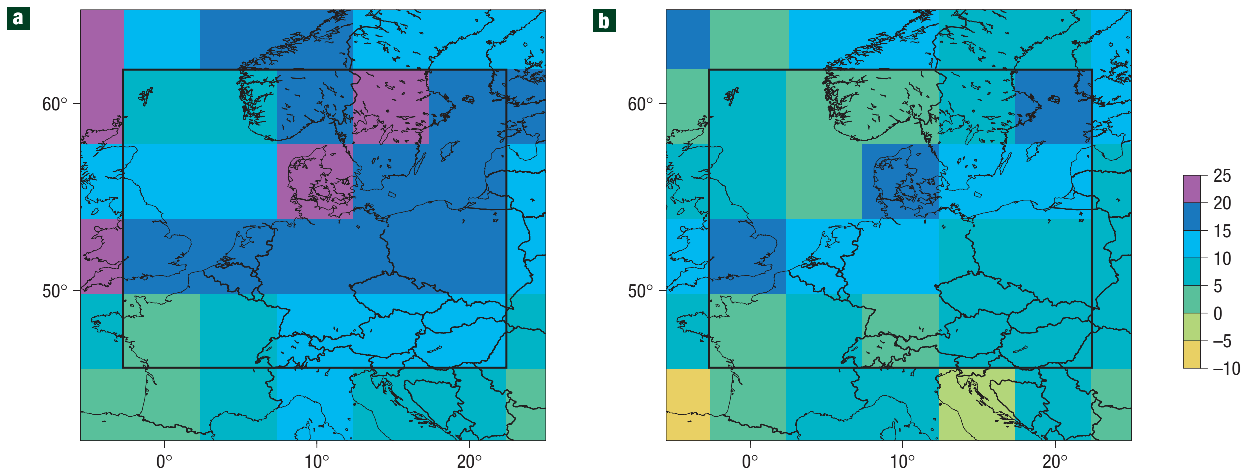

Figure 2 Normalized change of extreme hourly and daily summer precipitation in a climate change simulation. a,**b**, The 99.9th percentiles normalized by the local temperature rise (in % per °C) of the daily maximum of 1 h (**a**) and the 1 d precipitation intensity (**b**) for the pooled data of the 5 × 4 degrees longitude–latitude boxes. Intensity changes are computed from the future 2071–2100 period relative to the control 1971–2000 period. The square is the window for which we computed area averages (Table 1).

Table 1 Area average changes in extreme hourly ($I_{1\ \mathrm{hmax}}$) and daily precipitation (I_d). Relative change in different percentiles of precipitation extremes between 1971–2000 and 2071–2100 averaged over central Europe between 46 and 62 °N and −2 and 22 °E. I_pool is the total intensity change (in %) and $\Delta I_{\mathrm{pool},\,n}$ is the intensity change normalized by the temperature change (in % per °C).

	Hourly intensity				Daily intensity			
	95th	99th	99.9th	99.99th	95th	99th	99.9th	99.99th
ΔI_pool (%)	19.2	31.9	41.1	39.0	9.4	17.3	24.0	20.0
$\Delta I_{\mathrm{pool},\,n}$ (% per °C)	7.1	11.2	14.3	14.4	3.7	6.5	8.7	7.2

with the box mean temperature change between the control and the future period. For the 99.9th percentile, the modelled change in the 1 h extremes $I_{1\ \mathrm{hmax}}$ is clearly much larger than the change in 1 d extremes for large parts of central Europe (Fig. 2). For central Europe, changes in 1 h precipitation extremes are typically found to exceed 10%, in a large area even 15%, per degree. Daily extremes increase typically 5–10% per degree. The increase in intensity is smaller in France, which could be related to the much dryer average conditions in the future climate for that area (Supplementary Information, Fig. S3). Averages of this pooled data for a large central Europe area (between 46–62 °N and −2–22 °E) show that the changes typically obey the Clausius–Clapeyron relation for 1 d and two times the Clausius–Clapeyron relation for 1 h intensity changes (Table 1). Changes computed from the raw data on a grid point level give large spatial variations, but the average for central Europe is very similar to the average of the pooled data (Supplementary Information, Fig. S4 and Table S1).

The response of precipitation extremes to climate change and the dependency of precipitation extremes on temperature in the present-day climate are clearly not necessarily the same. On the one hand, the dependency in the present-day climate is derived from day-to-day variations in temperature and precipitation, which are both primarily caused by large-scale atmospheric circulation variability. On the other hand, a large part of the projected change in precipitation is not related to large-scale circulation changes[8,9,18]. In particular, the change of the extremes may be dominated by thermodynamically driven processes[8,18]. In such a conceptual framework of climate change, each (extreme) wet event in the present-day climate is considered to be related to a similar wet event in the future climate, occurring with a similar atmospheric circulation yet at a higher temperature and, thus, higher moisture content of the atmosphere. In this framework, the frequency of wet events does not change considerably, whereas we claim (without proof, but supported by the results) that the increase in intensity of each wet event can be predicted with the present-day scaling relations (Fig. 1).

In the present-day climate, the statistics of the large-scale atmospheric circulation is strongly related to temperature. In summer, the weather in the high temperature range is progressively dominated by dry atmospheric circulation types, resulting in a decrease of the fraction of wet days in the observed time series for De Bilt of typically 10–15% per degree for temperatures above 15 °C. Scaling relations based on the absolute frequency of the occurrence of precipitation extremes in the present-day climate implicitly contain this dependency. Application of these, absolute-frequency-based, scaling relations in estimating the response of extreme precipitation to climate change would unrealistically (over) emphasize the circulation effect compared with the thermodynamic effect. It is not unlikely that the atmospheric circulation will gradually change towards drier conditions as climate changes (decrease of wet days of 4% per degree on average in the regional climate model simulation), but it is unlikely that this is going to occur at the rate implied by the observed present-day time series (decrease of 10–15% per degree). In the absence of significant changes in the large-scale atmospheric circulation, the projected change in wet-day frequency is even likely close to zero[18]. We therefore used a scaling based on the frequency relative to the number of wet events (Supplementary Information, Figs S5–S7).

This work implies that changes in precipitation are not only controlled by the availability of precipitable water. For the globally average precipitation, this is already well known. GCMs give an increase at a rate of 1–3% per degree, which can be understood from energy budget considerations[4,14]. For local extremes, the small-scale dynamics of the cloud and sub-cloud layer as well as the cloud microphysics may also play an important role[1,19]. In present-day climate models, a large part of these processes is not resolved, and must be parameterized. Given this fact, it is encouraging to see that our regional model reproduces the super-Clausius–Clapeyron scaling for the most extreme events for a rather large temperature range. At the same time, model deficiencies in representing less extreme events and events in the highest temperature range are evident.

In the observations, the most pronounced temperature scaling is found for the most extreme hourly precipitation intensities. This suggests that on this timescale the processes involved are comparatively simple. Daily intensities show a more complex behaviour, indicating a complex interplay between processes at the daily level. On average, daily intensities increase at a slower rate with temperature than hourly intensities. But because hourly intensities naturally cannot exceed the daily sum, this distinction in scaling cannot hold infinitely. Interestingly, although there is no sign of a levelling off for hourly intensities, daily intensities indeed seem to increase steeply for temperatures above 22 °C (Fig. 1b,c).

Finally, the finding that the temperature scaling in the present-day climate (Fig. 1) is reflected in the modelled climate change signal (Fig. 2 and Table 1) opens ways of quantifying our confidence in future climate change predictions. In this respect, it is worrying that the model generally underestimates the temperature dependency (except for the most extreme events). Increases in extreme precipitation as climate changes may more generally follow a temperature dependency well above the Clausius–Clapeyron relation than suggested by present-day climate model results[17].

METHODS

The precipitation data of the period 1906–2004 has been carefully quality controlled and homogenized in the Dutch STOWA project[20]. The data set contains approximately 8.6×10^5 data points, of which 12/1/0.01% have intensities higher than $0.1/2/13\,\mathrm{mm\,h^{-1}}$. Hourly and daily intensities are both binned using the daily mean 2 m temperature. Daily mean temperatures are used, instead of 1 h temperatures, because we are interested in a proxy representing the temperature of the air mass. The hourly temperatures are to a large extent controlled by boundary-layer processes and radiation. The daily mean temperature in De Bilt in the period 1906–2004 ranges between $-15\,^{\circ}\mathrm{C}$ and 27 °C, with 7% of the days below 0 °C and 3% above 20 °C. The width of each bin is 2 °C. Wet events are defined by hours/days with a rainfall of more than $0.1\,\mathrm{mm\,h^{-1}}/0.1$ mm per day. The 99th and 99.9th percentiles are computed using a fit to a generalized Pareto distribution (GPD) to the upper 5% of the data. The confidence intervals are computed using the bootstrap. The 99th and 99.9th percentiles computed from the raw data fall within the confidence interval estimated from the bootstrap. Results obtained with a GPD fit to the upper 10% of the data are very similar; thus, the threshold used for the GPD fit is of minor importance. The 75th and 90th percentiles are computed from the raw data, and no confidence intervals are given.

The regional climate model[16] RACMO2 is operated at a resolution of 25 km. For the present-day climate (Fig. 1), RACMO2 was forced by boundaries derived from[21] ERA40. For the climate change simulation, RACMO2 was driven by output from the ECHAM5 global climate model using the A1b emission scenario for the period 1950–2100. This integration has been carried out in the EU-funded FP6 project ENSEMBLES[22]. For the temperature scaling, we used the output of 25 grid points close to De Bilt for the analysis.

Changes in precipitation per degree temperature α (in % per degree) are obtained by solving $P_{\mathrm{fut}} = (1+0.01\alpha)^{\Delta T} P_{\mathrm{con}}$, where ΔT is the temperature change and P_{con} and P_{fut} are the precipitation amounts in the control and future period, respectively. Area mean changes are computed using the geometric mean.

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Author contributions

The main idea and most analyses were by G.L and E.v.M. carried out the regional climate simulations and contributed to the text.

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