Extreme Sub-Hourly Precipitation Intensities Scale Close to the Clausius-Clapeyron Rate Over Europe

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Abstract Over sub-hourly time scales, extreme precipitation events play a critical role for many sectors impacted by climate change; however, it is unclear how these events will evolve in a warmer climate. Here, we perform climate simulations using a regional climate model over the greater Alpine region at kilometer-scale resolution. By analyzing precipitation intensities with short accumulation times, we show that the model can capture the observed percentiles of extreme sub-hourly precipitation measured at surface rain-gauge stations. Then, by simulating the future climate, we show that the associated increases in intensity of sub-hourly extreme precipitation events grow with the intensity of the events but tend asymptotically toward 6.5% per degree warming. This suggests that the most extreme intensities scale with the Clausius-Clapeyron scaling rate that represents the ability of a warmer atmosphere to hold more water vapor. It should be expected that these changes will lead to increased risks of flash flooding, land-slides, and erosion over Europe in a warmer climate.

Plain Language Summary The evolution of very short rain events in a warmer climate over a large part of Europe is addressed by using a regional climate model at very high resolution. We show that these events will intensify in a warmer climate and become about 6.5% more intense per degree of warming.

1. Introduction

Over sub-hourly time scales, extreme precipitation events are of paramount importance for a range of extreme events. They are the key driver of flash flooding (Archer & Fowler, 2018; Drobinski et al., 2014), strongly affect urban and mountain hydrology (Mastrotheodoros et al., 2020), play a key role for erosion (Willett, 1999), may trigger landslides and mud-flow events (Stoffel & Huggel, 2012), and represent a critical safety hazard for human infrastructure, bridges and dams. The importance of short-term events is due to the tremendous temporal and spatial variations of precipitation. In the case of a recent flash flood (June 11, 2018, Lausanne, Switzerland), the observed rainfall amounted to 41.3 mm in 10 min, corresponding to more than a third of the climatological monthly mean.

The response of precipitation to a warming of the climate system has been addressed in several studies. Generally, there is an overall agreement that the hydrological cycle will intensify in a warmer climate, which is a result predicted since some of the first climate modeling studies (Manabe & Stouffer, 1980). Overall, global climate models predict an increase in mean precipitation by about 2%–3% per degree warming (Held & Soden, 2006), which can be explained by global energy constraints (Allen & Ingram, 2002; Trenberth et al., 2009). Extreme precipitation, however, does not follow the same scaling, as global constraints do not apply. Indeed, studies show that extreme precipitation increases even in some regions where mean amounts decrease (e.g., Alpert et al., 2002).

The capacity of the atmosphere to hold moisture increases following the Clausius-Clapeyron (CC) rate of about 6%–7% per degree warming. If we assume that during an extreme precipitation event, the atmosphere will be close to saturation and that the event will precipitate the majority of the available moisture, one would expect that in a warmer atmosphere, such events will scale with the CC rate (O’Gorman & Schneider, 2009). This hypothesis has been supported by a wide range observational and numerical studies for daylong and hourly precipitation events (Ban et al., 2015; Fischer & Knutti, 2016; Pall et al., 2007; Rajczak & Schär, 2017; Scherrer et al., 2016; Westra et al., 2013). From a theoretical point of view, the CC scaling should apply as long as dynamical and microphysical feedbacks are weak, or if these feedbacks scale with
the local thermodynamic change given by the CC relation. However, for hourly and sub-hourly precipitation events, there are indications that precipitation extremes might scale at a faster rate (Lenderink & Van Meijgaard, 2008).

There has been a variety of studies looking at the scaling of extreme hourly precipitation in climate simulations using kilometer-scale models. The use of these models is favorable to coarser resolution models, as they represent dynamical processes in a more realistic way, improving several characteristics of precipitation (Armon et al., 2020; Prein et al., 2015; Schär et al., 2020). Kilometer-scale models explicitly resolve convective processes, and the parameterizations for deep convection can thus be turned off, reducing uncertainties that derive from semi-empirical formulations. Recent studies also demonstrate that switching off convection might be beneficial even at significantly lower grid spacings of around 10–20 km (Vergara-Temprado et al., 2020).

Studies using kilometer-scale models to investigate the scaling of hourly extreme precipitation extremes have started a few years ago (Ban et al., 2015; Kendon et al., 2014; Knist et al., 2020; Prein et al., 2017). They typically found a scaling close to the CC rate over land areas, although over some regions, for instance southern England, a stronger scaling was simulated (Kendon et al., 2014). Similarly, idealized simulations, using a uniform temperature shift and associated humidity increase, produced a scaling with up to about twice the CC rate (Lenderink et al., 2019). This enhanced scaling is usually referred to as super CC scaling. However, the simulated scaling rates of hourly precipitation over Europe can be reconciled with the CC scaling, provided the warming considered reflects that of the cloud layer, rather than that of the near-surface conditions. This difference originates from the fact that climate change not only leads to near-surface warming and moistening but also to pronounced stratification changes.

SuperCC scaling has also been observed in analyses of observed precipitation data over the Netherlands (Lenderink & Van Meijgaard, 2008) and in a number of other areas (Molnar et al., 2015; Westra et al., 2014). This reflects a remarkable property of observed precipitation time series, which is not yet fully understood. It is important, however, to point out that the so-detected superCC scaling cannot directly be extrapolated to a future climate, as the analyses use conditional wet-event percentiles (Schär et al., 2016).

Despite the societal importance of sub-hourly precipitation, the ability of kilometer-scale climate models to simulate these events and their evolution in future climates has only recently been studied (Chan et al., 2016; Loriaux et al., 2013; Meredith et al., 2020).

Here, we conduct 10 years-long simulations of current and future climates over the greater Alpine area. We first address the validity of our kilometer-scale models to represent sub-hourly precipitation events, by evaluating our simulations with rain gauge data. Then, the evolution of these events is addressed by looking at the scaling of sub-hourly extreme precipitation with the predicted increase in temperature as the climate warms.

2. Methods

2.1. Numerical Simulations

We perform two 10 years-long simulations using the regional COSMO model (Baldauf, 2013; Rockel et al., 2008; Steppeler et al., 2003) in its graphical processing unit (GPU) version (Fuhrer et al., 2014; Schär et al., 2020) over a large domain covering large parts of Europe centered in the Alps (Figure 1). The model uses a split-explicit third-order Runge-Kutta discretization in time in combination with a finite-difference scheme in space to solve the nonhydrostatic governing equations (Doms & Förstner, 2004). The employed set of parameterization schemes is similar as in Leutwyler et al., (2016), except for the use of a groundwater-runoff scheme (Schlemmer et al., 2018). Parameterized deep and shallow convection are turned off in the high-resolution grid. The cloud microphysics is represented with a 5-species bulk microphysics scheme. The model uses a timestep of 20 s.

The set-up of the simulation is similar as in Ban et al. (2014), but using a larger computational domain and a more advanced version of the model. The boundary conditions for the regional model are obtained from a climate simulation performed with the Max-Plank Institute (MPI) model (Stevens et al., 2013) for
the RCP8.5 emission scenario for the historical and end-of-the-century periods. The boundary fields are first fed every 6 h to a 12 km domain covering a large area of Europe (Figure S1). Then, the fields of the 12 km grid are fed with hourly frequency using a one-way nesting approach into our higher-resolution domain running at 2.2 km resolution (0.02°). We simulate two climate periods, one from 1st January 1996 to 1st January 2006 corresponding to present day climate (CTRL) and a future scenario period from 1st January 2090 to 1st January 2100 (SCEN). Soil moisture is spun up for 5 years in both the CTRL and SCEN simulations before the start of the simulation in the 12 km domain and for two additional months in the 2.2 km domain.

The model outputs precipitation fields on the 2.2 km grid every 6 min of simulation and several other fields at coarser time frequencies. For the analysis performed in Section 4, we define seven regions (Figure 1a) corresponding approximately to the regions presented in Christensen & Christensen, 2007 (usually known as PRUDENCE regions; Table S1).

2.2. Validation Data

For the evaluation of the control integration, we are using a subset of the Swiss automatic meteorological surface network (SwissMetNet, formerly ANETZ). The precipitation data is based on a tipping-bucket precipitation gauge with a bucket volume corresponding to 0.1 mm precipitation. The same subset of 24 stations as in Ban et al. (2014) is used, covering a large variety of orographic situations and altitudes. The data is available with a temporal frequency of 10 min. The location of the networks is shown in Figure 1b together with the model orography from the 2.2 km domain. The description of the meteorological stations is presented in the supplementary material (Table S2). In order to compare our high-resolution model to rain gauge stations, we use a similar approach as presented in Kaufmann (2008). The model gridpoint with the lowest height difference in a 4 km radius from the rain-gauge is directly compared with the station data. This approach has successfully been applied in Ban et al. (2014) for evaluating hourly precipitation intensities. To assess the climatological statistics of observed heavy precipitation events, a 20 years long period from 1st January 1995 to 1st January 2015 will be evaluated.

2.3. Statistical Analysis

For the analysis of the climate-change signal, precipitation percentiles are computed from the observed and simulated data. The analysis uses all-event percentiles, i.e., the percentiles are computed with respect to all events, irrespective of whether they are dry or wet, using several accumulation periods (from 6 min to 1 h). This choice is important as wet-event percentiles are conditional and may lead to statistical artifacts (Schär et al., 2016). For example, the most significant shift between current and future precipitation climates relate to changes in precipitation frequency (Polade et al., 2014) therefore making wet percentiles artificially affected by this change. More specifically, we calculate the percentile intensities $P_x$ for probabilities of $x = 99\%$, $99.9\%$, $99.99\%$, and $99.999\%$, using annual data series. To compute the precipitation scaling in % per K warming at specific percentiles, we use the 700 hPa temperature change $\Delta T$ averaged across each region during the season when the most extreme precipitation happen, and the change in precipitation intensity $\Delta P_x = P_{x,SCEN} - P_{x,CTRL}$ at every gridpoint between CTRL and SCEN periods. Then we compute the precipitation scaling ($S_x$) for each percentile as:
Which is expressed in percents per K warming. We then average the scalings over the subdomains of Figure 1a. We also calculate the corresponding inverse return period (see supplemental information for more details).

The use of the temperature change $\Delta T$ at a level of 700 hPa is selected to reflect changes in condensation level temperature instead of using 2 m temperature. This factor is important particularly over the British Isles. The sensitivity of the scaling to the selection of the condensation level temperature instead of the 2-m temperature was also pointed out in the study by Drobinski et al. (2016).

3. Evaluation

We first evaluate the reliability of the model to represent extreme precipitation in such sort time scales by using data from 24 rain-gauge stations from the MeteoSwiss’ automatic monitoring network (section 2.2). We use the 99%, 99.9%, 99.99%, and 99.999% percentiles of intense precipitation for each of the 24 stations over a 20 years long period from 1st January 1995 to 1st January 2015. As the model data are available with 6-min accumulation, and the observational data with 10-min accumulation, we aggregated the model data over 12 min. The respective 12-min percentiles are then scaled by a 5/6 factor for evaluation against the 10 min percentiles from the rain gauge stations. Performing a similar analysis with 6 min percentiles, scaled by a 5/3 factor, or excluding the last 10 years from the station data to match the simulated period did not change the results presented here. We should note that the historical simulation evaluated here is not driven by reanalysis but by a GCM, therefore it might inherit some of the GCM large scale biases.

Figure 2 presents the results of this evaluation for the extreme precipitation percentiles of all-year precipitation. The model is effectively able to produce similar values of extreme precipitation percentiles as observed by the 24 stations at 10 min periods across all the percentiles calculated (Figure 2a). This gives us reassurance in two aspects. First, the gridpoint to rain gauge method employed seems to be valid for evaluating the climatological characteristics of the meteorological stations, once the resolution of the model reaches the kilometer scale. Second, the model is effectively able to produce similar values of extreme precipitation percentiles as observed by the 24 stations at 10 min periods across all the percentiles calculated. This increases our confidence in the validity of the model dynamical and physical processes simulated for projecting the changes in future extreme precipitation events for very short aggregation times. The model also seems to be able to represent extreme precipitation intensities when the precipitation fields are aggregated in 30 min and hourly timesteps (Figures 2b and 2c), although the simulated intensities of 1-h events.
are underestimated in comparison to observations by about 20%. The overall satisfactory performance of
the model is consistent with the findings from Meredith et al. (2020), showing the ability of kilometer-scale
models to produce realistic subhourly extreme precipitation metrics. A similar evaluation using only sum-
mer season (June-July-August) percentiles is presented in the supplementary material (Figure S2) showing
similar results. This is to be expected as extreme precipitation over this region tends to be dominated by
the summer season. Therefore, the all-year percentiles are in fact reflecting mainly summer precipitation
events but with slightly smaller values for each percentile due to the inclusion of all the other season in the
calculation.

4. Climate Projections and Precipitation Scaling

Next, we consider the climate change signal for the RCP8.5 emission scenario for an end-of-the-century pe-
riod. Overall the simulation exhibits similar patterns as known from previous downscaling simulations (see
Figure S3). Summer 2 m temperature changes show a pronounced Mediterranean amplification, with the
warming in the Mediterranean amounting to about 4–5 K in comparison to 2–3 K in Northern Germany and
France, consistent with previous studies (Brogli et al., 2019). The projected change in precipitation climate
is characterized by a reduction of about 30% in mean precipitation, and an accompanying domain-mean
reduction in precipitation frequency (with daily precipitation > 1 mm/d) by about 37% (reduction in fre-
quency by about 20% in the Alpine region) (Figure S3b). Overall the climate-change signal is similar as with
conventional regional climate models as used in the CORDEX experiment (Rajczak & Schär, 2017).

We next look at the evolution of extreme precipitation in the future climate at hourly to subhourly time
scales. Our primary goal is to test whether the CC hypothesis continues to apply at subhourly accumulation
periods. For this purpose, we first calculate the percentiles of extreme precipitation for all-year precipitation
during the present and future simulation periods. The percentiles are first calculated using the 6 min pre-
cipitation output, then the precipitation fields are aggregated in time periods of (nonoverlapping) 12, 18, 24,
30, and 60 min to calculate the different scaling at coarser time scales. We make use of the regions defined
previously to perform our analysis.

The increase in precipitation intensity for each percentile at each gridpoint is then scaled by the regional
mean increase in temperature at 700 hPa and then averaged across each region. We use only land gridpoints
for our analysis, except for the Mediterranean region, in which we separate the contributions into two re-
gions, referring to sea gridpoints (Mediterranean Sea) and land gridpoints (Mediterranean Land). For each
region, the temperature used for normalization corresponds to the season when most extreme precipitation
events occur, that is autumn (September-October-November) for the Eastern Spain (ES) region and the
Mediterranean regions (MED and MED_SEA) and summer (June-July-August) for all the other regions.

The scaling results are presented in Figure 3. For all the regions studied, we observe that hourly extreme
precipitation approaches, but does not exceed the CC rate. In other words, changes in heavy precipitation
events increase with the event size and are simulated to be constrained by the CC limit in the range of per-
centiles considered. Sub-hourly precipitation intensities, interestingly, scale at a similar or slightly lower
rate than the hourly precipitation intensities, suggesting that short time scale dynamical amplifications
might not play a significant role for the scaling of precipitation intensities in the future climate, for the
region and accumulation periods considered. It should be noted that over some regions (Eastern Spain,
France, and South East Britain) the scalings for the most extreme percentile are about 2% lower than the CC
limit even at the most extreme percentile. Although this could be seen as a disagreement with the CC ap-
proach, there is still a clear increase in the scaling rate as the intensity percentiles get more extreme. There-
fore, one could expect that moving toward even more extreme percentiles in these regions might make the
scalings increase closer to the CC limit. We should also note, however, that other dynamical factors might
also help to explain these differences (Emori & Brown, 2005; Pfahl et al., 2017).

When converting the percentiles into inverse return periods (Figure S4), it can be seen that the scalings
calculated align giving a larger agreement between them at different time aggregations for a similar return
period. This is caused as a given percentile value represents a different rareness of an event depending
on the aggregation time. Therefore, we should expect a certain lag in the scaling rates when comparing
percentiles with different aggregation times as observed in Figure 3. The difference in scaling between
hourly precipitation and 6-min precipitation is also strongly related to the absolute intensity of the events. Figure S5 shows the difference between the scaling of hourly precipitation and 6-min precipitation at the 99.99% percentile in each region. A negative trend can be observed in which the scaling values get closer to each other in regions with stronger absolute values of hourly precipitation intensities. This also supports the idea of an asymptotic value toward which the scaling of extreme precipitation gets limited for hourly and sub-hourly time scales.

When the scaling rates are normalized using 2-m temperature changes (Figure S6), the CC relation is slightly surpassed for the British Isles, the mid-Europe region and the Mediterranean regions due to the strong stratification change found in the vertical temperature projections (Figure S7).

These results suggest that even for very short and extreme rain events, a superCC scaling is not expected to happen over large parts of Europe. The projected increase in extreme precipitation happens together with an overall decrease in summer mean precipitation (Figure S3b) as temperature increases. This behavior can be explained as both convective inhibition (CIN) and convective available potential energy (CAPE) increase as climate warms (Figure S3d and S3c), therefore making rain less frequent (Figure S3e) but more intense (Figure S3f). Looking at hourly precipitation instead of daily shows a similar behavior (Figure S8). In general, high-CAPE high-CIN situations are considered good predictors for severe weather and thunderstorms (Schneider & Dean, 2008). High CAPE reflects the presence of moist convective energy in the boundary layer, while high CIN confines the build-up over a sufficiently long period before the energy is released in afternoon thunderstorms.

5. Summary

We have performed kilometer scale simulations to study and evaluate the intensity percentiles of sub-hourly extreme precipitation events. By using long-term station data of precipitation amounts every 10 min, we have shown that our kilometer-scale model simulations are effectively able to simulate the percentiles of extreme precipitation intensities at sub-hourly and hourly time scales. We argue therefore that our model is suited to study the evolution of extreme precipitation events as the climate warms. By conducting climate simulations for the end of the century using an upper end emission scenario, we find that changes in extreme precipitation intensities at hourly and sub-hourly scales increase with the magnitude of the event and tend asymptotically toward the rate set by the atmospheric capacity to hold water vapor (i.e., the CC rate) across all regions considered. This suggests that changes in heavy precipitation events will be constrained by the CC scaling. Using the temperature increase at cloud level (700 hpa) to normalize the scalings instead of 2-m temperature is an important factor to quantify the scaling.

We did not find any indication that extreme short-term events might intensify at a superCC rate (i.e., increase faster than the water-holding capacity of the ambient air), in any of the studied regions. This indicates that the enhancement of short-term precipitation intensity by dynamical or microphysical feedbacks seems to be negligible in our model simulations for the region considered. This study confirms previous results regarding the intensification of hourly precipitation events with climate change (Ban et al., 2015), and it provides evidence that the same also applies to subhourly precipitation.

However, we should note that the current understanding of the mechanisms of extreme precipitation events are still limited, therefore the results might be model dependent and further study should be conducted on this topic. For instance, by using higher computational resolution and/or more advanced microphysics schemes. In addition, our study has only considered a comparatively small geographic area and one particular large-scale climate model. Despite these limitations, the current results are among the first of their kind and of significant interest to climate-change adaptation measures.

Figure 3. Scaling of extreme precipitation percentiles for different accumulation periods across the different regions presented in Figure 1a and defined in Table S1. The scaling expresses the difference between the future and current climate simulations in % per K warming. The temperature used for the scaling corresponds to the 700 hpa level temperature. The gray band highlights the range of the Clausius-Clapeyron scaling (6%–7%/K). (a) Alpine region, (b) France, (c) Eastern Spain, (d) Mid-Europe, (e) Eastern Europe, (f) South East Britain, (g) Mediterranean Sea, (h) Mediterranean Land. The percentiles are computed for the all-year percentiles and normalized with the temperature increase (at 700 hpa) of the season with the most intense precipitation happens (for all regions this is June-July-August, except for Eastern Spain and the Mediterranean (MED) regions where this is September-October-November). The absolute values of the percentiles for the historical and scenario simulation are shown in Figures S9 and S10 in the supplementary material. The temperature projections at each season for each region are also shown in Figure S11 and the fraction of events overpassing the most extreme percentile per season are shown in Figure S12.
Data Availability Statement
The data used for the main results of this study can be accessed at a public github repository (https://doi.org/10.5281/zenodo.4010228). The full model simulations are stored in the Jülich Center for Supercomputing as part of the CORDEX-FPS-convection study and are publicly available by requesting access to the system administrators (more info at https://cordex.org/data-access/how-to-access-the-data/). The observational data used can be accessed from the IDAWEB system at MeteoSwiss (https://gate.meteoswiss.ch/idaWEB/login.do).

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