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- Extreme hourly precipitation intensifies with the Clausius-Clapeyron scaling

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- Figures S1–S8

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Heavy precipitation in a changing climate: Does short-term summer precipitation increase faster?

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Abstract Climate models project that heavy precipitation events intensify with climate change. It is generally accepted that extreme day-long events will increase at a rate of about 6–7% per degree warming, consistent with the Clausius-Clapeyron relation. However, recent studies suggest that subdaily (e.g., hourly) precipitation extremes may increase at about twice this rate. Conventional climate models are not suited to assess such events, due to the limited spatial resolution and the need to parametrize convective precipitation (i.e., thunderstorms and rain showers). Here we employ a convection-resolving model using a horizontal grid spacing of 2.2 km across an extended region covering the Alps and its larger-scale surrounding from northern Italy to northern Germany. Consistent with previous results, projections using a Representative Concentration Pathways version 8.5 greenhouse gas scenario reveal a significant decrease of mean summer precipitation. However, unlike previous studies, we find that both extreme day-long and hour-long precipitation events asymptotically intensify with the Clausius-Clapeyron relation. Differences to previous studies might be due to the model or region considered, but we also show that it is inconsistent to extrapolate from present-day precipitation scaling into the future.

1. Introduction

Changes in short-term precipitation events are of great interest due to potentially important hydrological impacts such as flash floods, erosion, landslides, and debris flows. These concerns particularly apply to mountainous regions, where such perils are rather common under current climatic conditions.

Past research has shown that thermodynamic considerations may help to assess potential future changes in precipitation extremes. More specifically, the saturation water vapor pressure in the atmosphere is a function of air temperature and increases at a rate of 6–7% per degree of surface warming according to the Clausius-Clapeyron relation. Theoretical studies suggest that extreme precipitation events may increase at this rate, while mean global precipitation increases at a slower rate of 1–3% per degree, due to energy constraints [*Allen and Ingram*, 2002; *O'Gorman and Schneider*, 2008]. Recent studies using rain gauge observations suggest that increases of subdaily (e.g., hourly) precipitation extremes may even exceed the expectations from the Clausius-Clapeyron relation [*Lenderink and van Meijgaard*, 2008; *Berg et al.*, 2013; *Loriaux et al.*, 2013] (referred to as superadiabatic scaling). The concerns about such superadiabatic increases have further been raised by recent modeling studies [*Lenderink and van Meijgaard*, 2008; *Kendon et al.*, 2014], which projected future increases at high precipitation percentiles well in excess of the Clausius-Clapeyron scaling. On the other hand, paleoclimate reconstructions of floods using Alpine lake sediments find a lower incidence of large-scale heavy precipitation events during periods of elevated ambient temperature [*Glur et al.*, 2013], but this might still be consistent with increases in short-term small-scale events.

The projected changes in precipitation are associated with complex regional patterns [*O'Gorman and Schneider*, 2009a]. A particularly important example is the summer climate in the southern part of the European continent, where mean precipitation is projected to decrease [*Collins and Knutti*, 2013], while heavy precipitation might increase [*Christensen and Christensen*, 2003]. One difficult challenge behind such projections is the representation of atmospheric convection in climate models [*Fischer et al.*, 2014]. The scaling of extreme precipitation in current climate models is quite inconsistent, ranging from 1.3%/K to 30%/K [*O'Gorman and Schneider*, 2009b], probably due to different representations of deep convection. The resolution of conventional climate models is too coarse to explicitly resolve convective processes, and they thus use parameterizations instead. This leads to a poor representation of the diurnal cycle of summer precipitation [*Dirmeyer et al.*, 2012; *Hohenegger et al.*, 2008], and to an underestimation of the frequency and intensity of heavy hourly events [*Ban et al.*, 2014]. The inability to represent extreme hourly precipitation

Table 1. Statistical Diagnostics of Daily and Hourly Precipitation Used in This Study[a]

Abbreviation	Full Name	Definition
p97.5D	Heavy daily precipitation	The 97.5th percentile of daily precipitation
p99D	Extreme daily precipitation	The 99th percentile of daily precipitation
p97.5H	Heavy hourly precipitation	The 97.5th percentile of hourly precipitation
p99.9H	Extreme hourly precipitation	The 99.9th percentile of hourly precipitation
p99.99H	Extreme hourly precipitation	The 99.99th percentile of hourly precipitation

[a] Note that all percentile indices are expressed relative to all (wet and dry) days/hours.

ultimately leads to the underestimation of the observed scaling rate, especially over complex terrain [*Ban et al.*, 2014].

To overcome the aforementioned deficiencies, an attractive approach is the use of convection-resolving models. These models operate at very high resolution (grid spacing between 1 and 3 km) where convective processes can be represented explicitly based on the governing dynamical equations and without the need for a convection parameterization. It has been shown that this approach improves the simulation of the diurnal cycle of summer precipitation [*Ban et al.*, 2014; *Hohenegger et al.*, 2008; *Kendon et al.*, 2012; *Prein et al.*, 2013], the simulation of heavy hourly events [*Ban et al.*, 2014; *Kendon et al.*, 2012], and the representation of the precipitation scaling with temperature [*Ban et al.*, 2014]. Due to the high computational costs, the use of convection-resolving models in climate studies is very limited, typically restricted to relatively small domains [*Knote et al.*, 2010; *Kendon et al.*, 2012, 2014; *Prein et al.*, 2013; *Chan et al.*, 2014a], and often to only a few summer seasons [*Hohenegger et al.*, 2008; *Prein et al.*, 2013; *Knote et al.*, 2010].

One of the first convection-resolving climate change projections simulating several decades across the southern UK projects a future intensification of short-duration precipitation in summer [*Kendon et al.*, 2014], while across a relatively small domain in Germany results are inconclusive due to strong influence of boundary data [*Knote et al.*, 2010]. Another line of research has used convection-resolving models in idealized settings to investigate the nature of precipitation scaling [*Romps*, 2011; *Muller et al.*, 2011; *Singh and O'Gorman*, 2014].

Here we present projections of precipitation using a convection-resolving model covering an extended Alpine region (1100 km × 1100 km) at a horizontal resolution of 2.2 km. To our knowledge, this is one of the first convection-resolving climate change experiments over such a large domain and for such a long time period (10 yearlong time slices of control and scenario periods). Since a 10 year period is generally considered too short to provide projections, we compare the convection-resolving model against a conventional model driven by the same large-scale forcing, but covering 30 years.

2. Methods

2.1. Model Setup

The model used is the Consortium for Small-Scale Modeling in Climate Mode (COSMO-CLM) model [*Steppeler et al.*, 2003] in a setup that is close to its current use in numerical weather prediction [*Baldauf et al.*, 2011]. The COSMO-CLM model has recently been validated using long-term (10 years) convection-resolving climate simulations [*Ban et al.*, 2014]. The same setup is used in the current study. The COSMO-CLM model is used at a convection-resolving resolution of 2.2 km (CRM2) across the greater Alpine region. The lateral boundary and initial conditions for CRM2 come from COSMO-CLM at 12 km resolution where convection is parameterized (convection-parametrized model, CPM12). CPM12 covers Europe and is driven by lateral boundary conditions from the Earth System Model of the Max-Planck-Institute (MPI-ESM-LR) [*Stevens et al.*, 2013]. CRM2 and CPM12 are run for a 10 yearlong current (1991–2000; control (CTRL)) and future periods (2081-2090; scenario (SCEN), using an Representative Concentration Pathways version 8.5 (RCP8.5) greenhouse gas scenario). In addition, the much cheaper CPM12 model is also run for 30 yearlong present and future periods.

The soil-moisture in CPM12, both in the control and the scenario simulation, is initialized with the soil-moisture climatology from the Era-Interim-driven 10 yearlong CPM12 simulation [*Ban et al.*, 2014]. In addition, CPM12 is initialized 5 years, and CRM2 2 months, prior to the analysis periods, in order to ensure a proper spin-up of soil-moisture.

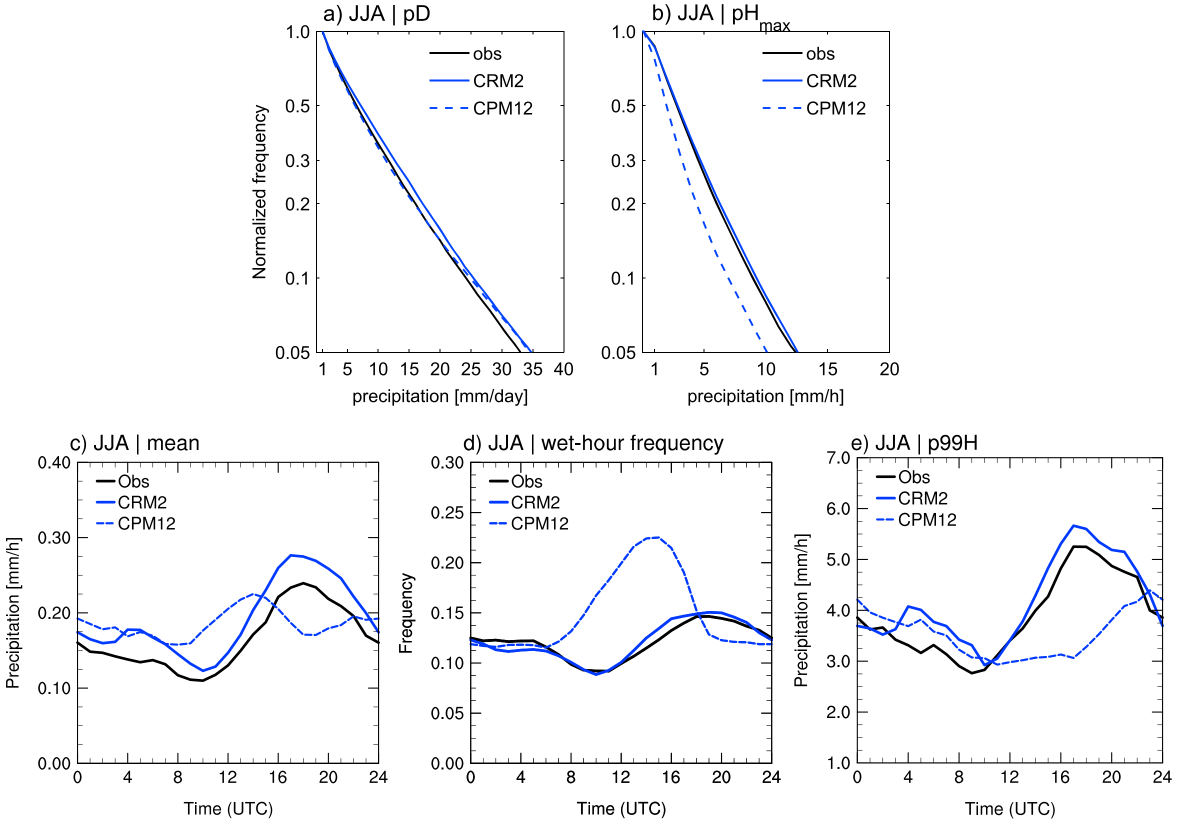

Figure 1. Validation of summer (June–August) precipitation for reanalysis-driven simulations with 12 km (CPM12, dashed blue) and 2.2 km horizontal resolution (CRM2, solid blue). Cumulative distributions of (a) daily precipitation and (b) daily maximum 1 h precipitation, expressed relative to the number of wet days. Mean diurnal cycle of (c) mean precipitation, (d) wet-hour frequency, and (e) heavy hourly precipitation (*p99H*, 99th percentile of all hours). The validation is performed using ERA-Interim-driven simulations against 62 Swiss rain gauge stations in the period 1998–2007.

2.2. Analyses

Validation Data. The validation follows a previous study [*Ban et al.*, 2014] but uses an extended set of 62 rain gauge precipitation stations in Switzerland that operate at hourly resolution throughout the 1991–2000 period and entails a more detailed analysis of the diurnal cycle. As in *Ban et al.* [2014], the model data are interpolated to the station locations using nearest neighbor interpolation for CPM12, while for CRM2 the grid point with the smallest difference to the station altitude within a 4 km search radius is selected. The thresholds for daily and hourly precipitation observations are 1 mm/d and 0.1 mm/h, respectively, below which precipitation is not recorded.

In some of the analysis we are also using daily maximum 1 h precipitation. This quantity is defined, for each day, as the maximum hourly precipitation rate of the 24 hourly values.

Extreme Indices. To analyze the simulations, we employ a series of extreme indices defined in Table 1.

In our study, all percentile indices are expressed relative to all days/hours, including dry days/hours. This method differs from many previous studies that used indices where only wet days (or hours) are taken into account (e.g., $p95D_{WET}$ and $p95H_{WET}$). The practice to express percentiles relative to wet days (defined as days with precipitation $>$ 1 mm) or wet hours (defined as hours with precipitation $>$ 0.1 mm), respectively, originates from observational studies, as small precipitation amounts are difficult to measure by rain gauges and thus need to be excluded from the analysis of observational data. The use of percentiles relative to wet days has been recommended [*Klein Tank et al.*, 2009; *Zhang et al.*, 2011] and is common in climate change studies [*Christensen and Christensen*, 2003; *Rajczak et al.*, 2013; *Sillmann et al.*, 2013; *Kendon et al.*, 2014]. he procedure is very common and some studies do not even explicitly state whether they use a wet-day threshold to express percentiles. Analyses of indices such as $P95D_{WET}$, however, may be misleading, as changes in the fraction of wet days may mimic changes in extremes (see Figure S5 in the supporting information). Increases in the fraction of dry days (as projected for summer in southern Europe) lead to

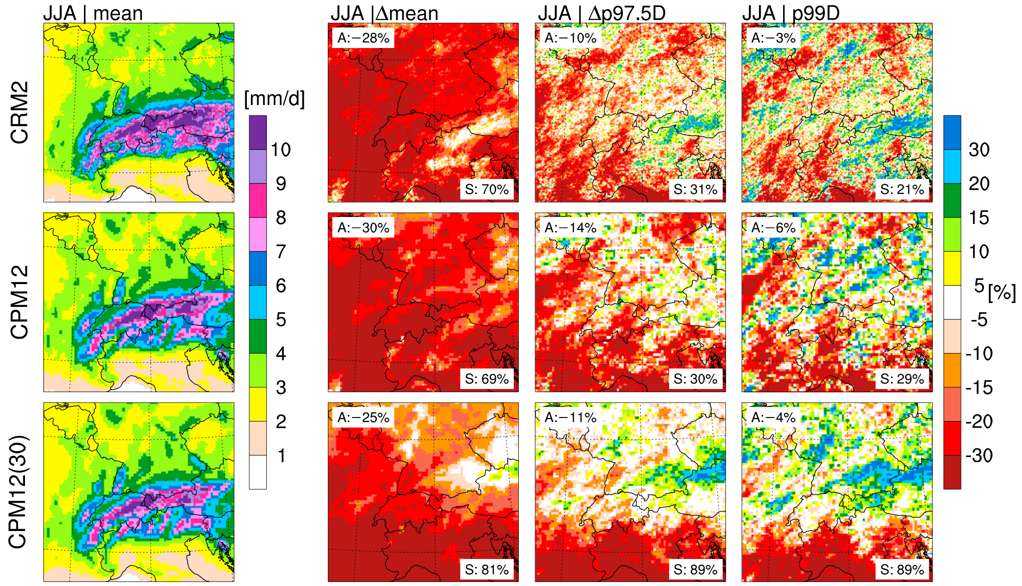

Figure 2. Summer precipitation on daily time scales. Results are shown for absolute (first column) mean precipitation (mean) in CTRL, and projected changes (second column) in mean precipitation (Δmean), (third column) in heavy daily precipitation (Δ*p97.5D*), and (fourth column) in extreme daily precipitation (Δ*p99D*), obtained (top row) for CRM2, (middle row) for CPM12, and (bottom row) for a 30 years long CPM12 run. Changes are expressed as difference between SCEN (2081–2090) and CTRL (1991–2000) simulations normalized by CTRL. Domain mean changes are indicated in the top left corner of the panels, while the percentage of grid points with statistically significant changes at the 95% level is indicated in the bottom right corner of the panels. Here *p97.5D* and *p99D* denotes the 97.5th and 99th percentile of daily precipitation relative to all (wet and dry) days.

increases of $P95D_{\mathrm{WET}}$, seemingly indicating increases in heavy events, while the change in $P95D_{\mathrm{WET}}$ may merely be due to a decreases of weak and intermediate precipitation events. Likewise, decreases in the fraction of dry days (as, e.g., projected for winter in Scandinavia) may underestimate the increase in heavy events. These biases may be substantial (see Figure S6 in the supporting information) and are avoided with the indices used in the current study.

Statistical Significance. To test the significance of the future changes, the Wilcoxon-Mann-Whitney test [*Wilks*, 2011] is applied on a series of events that exceed different thresholds.

3. Results

3.1. Validation

For validation of the convection-resolving model, an additional 10 year simulation is conducted using lateral boundary forcing from the ERA-Interim reanalysis [*Dee et al.*, 2011] for the period 1998–2007. The reanalysis represents the actual large-scale weather evolution as closely as possible. In addition, validation of the global climate model (GCM)-driven simulations can be found in the supporting information (Figures S1–S3). Validation is conducted against a set of 62 Swiss rain gauge stations that provide hourly data during the 10 year period. Results reveal close agreement of CRM2 and CPM12 regarding the frequency of daily precipitation events (Figure 1a), and a major improvement of the simulation of hourly precipitation with CRM2 (Figure 1b). In particular, CRM2 is able to capture the frequency of heavy hourly precipitation events, while CPM12 underestimates it significantly.

Figures 1c–1e highlight aspects of the diurnal cycle in terms of mean and heavy precipitation amounts (see section 2 for definition of percentile indices) and wet-hour frequency. Here the diurnal cycle of heavy precipitation (Figure 1e) is based on the 99th hourly percentiles (p99H) calculated using all hourly data. In Figures 1a–1e, CRM2 realistically simulates the amplitude and phase of the diurnal cycle, while CPM12 fails to reproduce the observed diurnal cycle. For instance, CPM12 simulates the peak of heavy events in the night and early morning hours, while in reality the maximum is in the late afternoon. These biases go along with an overestimation of the frequency of convective events (Figure 1d), indicating a too weak intensity of precipitation peaks in the diurnal cycle, and this is a characteristic problem of many convection schemes.

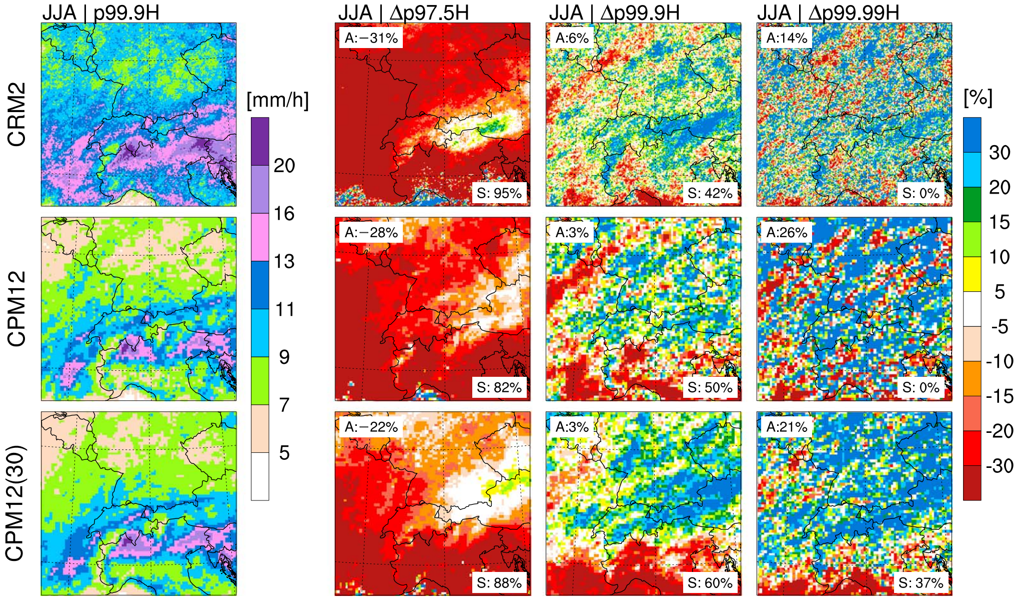

Figure 3. Summer precipitation on hourly time scales. Results are shown for (first column) extreme precipitation (*p99.9H*) in CTRL simulation, change (second column) in the heavy precipitation (Δ*p97.5H*), and (third and fourth columns) in extreme precipitation (Δ*p99.9H* and Δ*p99.99H*) obtained for (top) CRM2, (middle) for CPM12, and (bottom) for a 30 years long CPM12 run. Changes are expressed as difference between SCEN (2081–2090) and CTRL (1991–2000) simulations normalized by CTRL. Domain mean changes are indicated in the top left corner of the panels, while the percentage of grid points with statistically significant changes at the 95% level is indicated in the bottom right corner of the panels. Here *p97.5H*, *p99.9H*, and *p99.99H* denote percentiles of hourly precipitation relative to all (wet and dry) hours.

Overall the performance of CRM2 exhibits a dramatic improvement. It is probably the first time that the diurnal cycle of heavy summer precipitation in a convection-resolving model has been analyzed in a climatological sense using surface data, and it is highly encouraging to see how a better representation of convection leads to such a significant gain in skill, without the use of any tuning or calibration.

3.2. Climate Change Projections

Next we turn attention to the climate change signal obtained from simulations driven by a free-running GCM under an RCP8.5 greenhouse gas and aerosol scenario. Aspects of seasonal mean and daily precipitation extremes are discussed along Figure 2, while hourly precipitation extremes are dealt with in Figure 3. Comparison between CRM2 and CPM12 (Figures 2, top row, and 2, middle row) reveals close agreement in terms of mean summer precipitation amounts (Figure 2, first column) and projected changes in mean summer precipitation (Figure 2, second column). In particular, both models capture the pronounced Alpine precipitation anomaly and project a domain mean decrease of precipitation by 28 to 30%. Figures 2 (third column) and 2 (fourth column) show changes in heavy daily precipitation (Δ*p97.5D*, see caption and section 2 for definition) and change in the extreme daily precipitation (Δ*p99D*). These two indices relate to the precipitation of the top 2.25 and 0.9 days per summer season, respectively. Both modeling systems produce qualitatively similar results, namely, a decrease of heavy and extreme precipitation. The decrease is smaller for higher percentile.

More detailed analysis at higher percentiles shows slight increases in the frequency and intensity of daily extremes (Figures 4a and 4c). The frequency distribution changes shown in this figure are calculated by pooling all daily precipitation data from all grid points across the CRM2 domain, and then by determining the relative change in the frequency of grid point events that exceed the given thresholds.

We continue by considering projections of hourly extremes (Figure 3). Comparison of the climate change signal between the two models on hourly time scales reveals close agreement regarding decreases of heavy (Δ*p97.5H*) and increases of extreme (Δ*p99.9H* and Δ*p99.99H*) hourly precipitation. The aforementioned percentile indices (*p97.5H*, *p99.9H*, and *p99.99H*) approximately relate to the precipitation of the top 50 and the top 2 h per summer season, and the top two hours per 10 summer seasons, respectively. Although extreme hourly precipitation (Δ*p99.9H*) increases faster in CRM2 than in CPM12, the domain mean increase

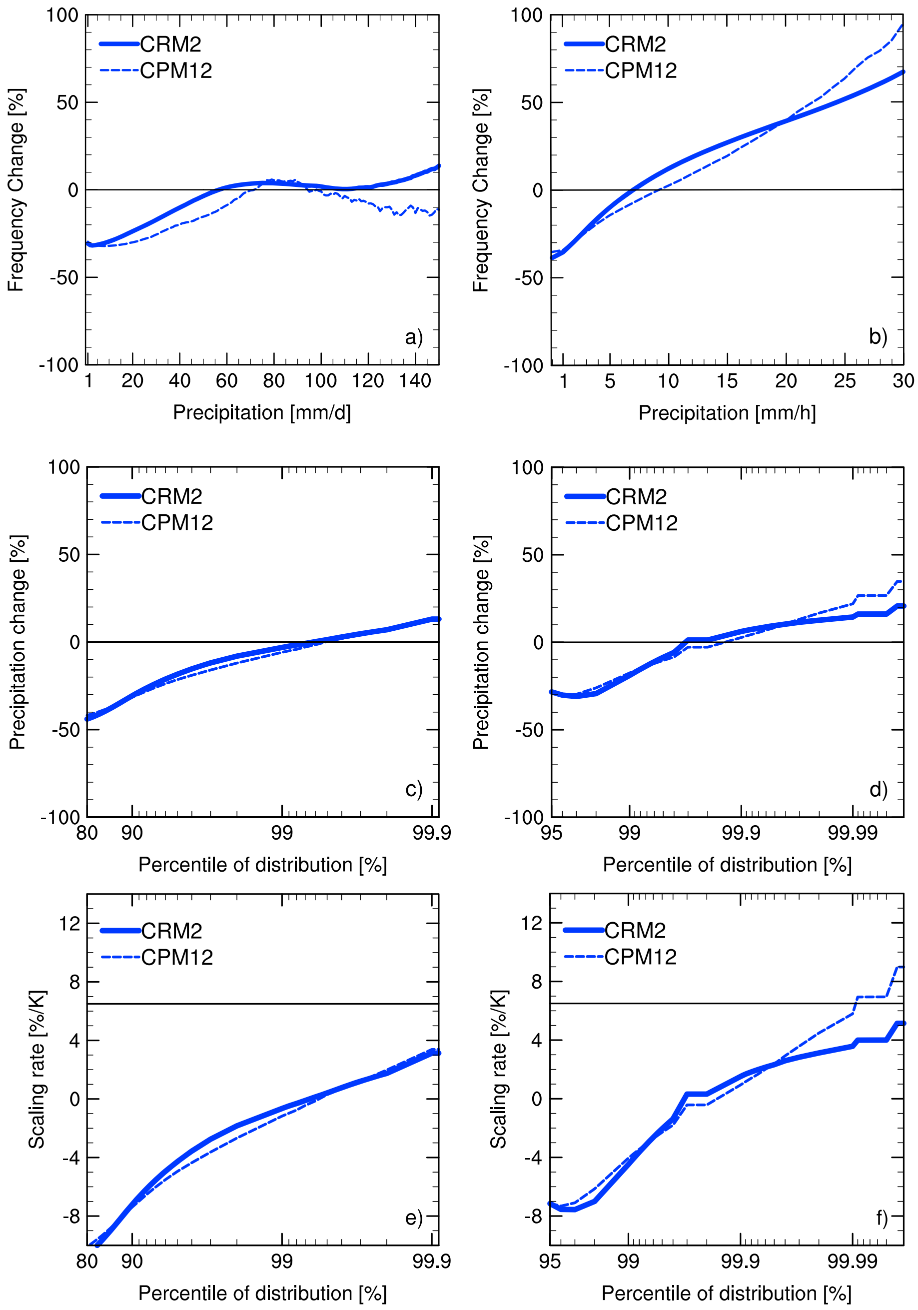

Figure 4. Projected changes in the (a and b) frequency distribution of precipitation and (c–f) precipitation at high percentiles on daily (Figures 4a, 4c, and 4e) and hourly (Figures 4b, 4d, and 4e) time scales in summer. Figures 4a and 4b show the projected changes in frequency distributions for CRM2 (solid lines) and for CPM12 (dashed lines). Figures 4c and 4d show the projected relative changes of precipitation at high percentiles. Figures 4e and 4f show the relative change in high percentiles of precipitation normalized by the local temperature change (in percent per degree warming). The regional averaging in Figures 4a and 4b is based on the pooling of all grid points across the CRM2 domain, while in Figures 4c–4f, it is based on the spatial average of the grid point relative changes and scaling rates.

amounts to merely 3–6% at the 99.9th percentile. This is smaller than found by a previous study for the southern UK [*Kendon et al.*, 2014], which found a much stronger increase at a significantly smaller percentile (on average a 36% increase of heavy rainfall; mean of the upper 5% of wet events).

Next we analyze changes in the frequency of hourly precipitation as a function of precipitation intensity (Figure 4b). In particular, Figure 4b shows that the frequency of extreme hourly precipitation increases strongly for events above 10 mm/h, with increases for 20 mm/h events amounting to as much as 40%. The frequency increase is smaller in the CRM2 simulations for precipitation intensities above 20 mm/h.

Overall, the increases in extreme hourly and daily precipitation intensities are substantially smaller than seen in previous studies [*Lenderink and van Meijgaard*, 2008; *Kendon et al.*, 2014]. In our simulations, the increase of precipitation events in CRM2 is consistent with the expectations from the Clausius-Clapeyron relation [*Allen and Ingram*, 2002] (Figures 4e and 4f), i.e., the increase of the most extreme events appears to converge to a value of about 6.5%/K. This implies that on the regional scale both daily and hourly precipitation extremes are constrained by the Clausius-Clapeyron relation, that is, by moisture availability. This is in contrast to some previous studies that find a superadiabatic scaling for extreme events. These discrepancies might in principle be due to different models and regions considered, but we also demonstrate that they can at least partly be traced back to an inconsistent use of extreme indices (see section 2 and supporting information).

The CPM12 model reveals the same results for daily (Figure 4e), but not for hourly precipitation (Figure 4f), where for the events above the 99.95th percentile a stronger increase, exceeding the expectations from Clausius-Clapeyron relation, is projected (Figures 4d and 4f). Despite a general underestimation of intermediate and heavy events (Figure 1b), convection-parameterizing models tend to overestimate extreme precipitation (see Figure S7 in the supporting information) [*Chan et al.*, 2014b; *Williamson*, 2013], and this contributes to the low confidence in these models.

To handle the computational effort of the convection-resolving model, our simulations had to be restricted to 10 year periods. To assess whether decadal variability has a significant impact, Figures 2 and 3 (bottom rows) shows results for a 30 year CPM12 simulation covering the periods 2071–2100 versus 1976–2005. It can be seen that the results are very similar to the corresponding 10 year simulation (Figures 2 and 3, middle rows), although there are some regional differences. Overall, this indicates that decadal variability is not crucial for our analysis, at least for the region and time periods considered.

4. Conclusion

Consistent with conventional climate models [*Collins and Knutti*, 2013], high-resolution climate change simulations project pronounced decreases in mean summer precipitation over middle and southern Europe. We demonstrate that this decrease is associated with frequency reductions of small and intermediate precipitation events. On daily and hourly time scales, heavy events are projected to become more frequent and more intense, but not as pronounced as in some previous studies. In particular, in distinction to previous studies, we find that even at hourly time scales these increases are consistent with the Clausius-Clapeyron scaling, i.e., with an intensity increase of up to 6–7% per degree warming. Our analyses did not reveal any indication of a faster (superadiabatic) intensity increase with changing climate, although our model replicates the respective scaling for the current and future climate [*Ban et al.*, 2014] (see also Figure S8 in the supporting information). The inability to extrapolate from present-day superadiabatic scaling into the future is due to changes in the fraction of wet hours (see Figure S4 in the supporting information).

Our results are of significant importance, since they suggest that a comparatively simple scaling relationship can be used as a tool for climate change adaptation in the area of heavy precipitation. In particular, it is highly remarkable that the projected percentage increases in high-percentile hourly events exhibit comparatively little geographical structure (Figure 3), despite the presence of complex topography and pronounced patterns in absolute precipitation amounts.

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