



# The influence of convection-permitting regional climate modeling on future projections of extreme precipitation: dependency on topography and timescale

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## Abstract

Owing to computational advances, an ever growing percentage of regional climate simulations are being performed at convection-permitting scale (CPS, or a horizontal grid scale below 4 km). One particular area where CPS could be of added value is in future projections of extreme precipitation, particularly for short timescales (e.g. hourly). However, recent studies that compare the sensitivity of extreme hourly precipitation at CPS and non-convection-permitting scale (nCPS) have produced mixed results, with some reporting a significantly higher future increase of extremes at CPS, while others do not. However, the domains used in these studies differ significantly in orographic complexity, and include both mountain ranges as well as lowlands with minimal topographical features. Therefore, the goal of this study is to investigate if and how the difference between nCPS and CPS future extreme precipitation projections might depend on topographic complexity and timescale. The study area is Belgium and surroundings, and is comprised of lowland in the north (Flanders) and a low mountain range in the south (Ardennes). These two distinct topographical regions are separated in the analysis. We perform and analyze three sets of 30 year climate simulations (hindcast, control and end-of-century RCP 8.5) at both nCPS (12 km resolution) and CPS (2.5 km resolution), using the regional climate model COSMO-CLM. Results show that for our study area, the difference between nCPS and CPS future extreme precipitation depends on both timescale and topography. Despite a background of general summer drying in our region caused by changes in large-scale circulation, the CPS simulations predict a significant increase in the frequency of daily and hourly extreme precipitation events, for both the lowland and mountain areas. The nCPS simulations are able to reproduce this increase for hourly extremes in mountain areas, but significantly underestimate the increase in hourly extremes in lowlands, as well as the increase in the most extreme daily precipitation events in both the lowland and mountain areas.

## 1 Introduction

As the temperature of the Earth's atmosphere is expected to increase significantly, so is its water vapor content. Modeling studies estimate a global mean increase in atmospheric water vapor of 5–25% by the end of the century, depending

on carbon emission scenario (Collins et al. 2013). Consequently, global precipitation is expected to increase as well (Pfahl et al. 2017). However, changes in precipitation will not be spatially uniform, but are expected to vary regionally, due to simultaneous shifts in global circulation patterns (Collins et al. 2013). For Western Europe, modeling studies generally project that mean summer precipitation will decrease, whereas mean winter precipitation is expected to increase (Jacob et al. 2014). Of course, not only the future change in mean seasonal precipitation is of interest, as possible future changes in occurrence and intensity of extreme precipitation can have a strong societal impact as well (Easterling et al. 2000; Rosenzweig et al. 2002; Ciscar et al. 2011). Note that extreme precipitation intensity could increase even if mean precipitation in a region decreases (e.g. for Western Europe in summer), as the future atmosphere will be warmer and thus able to hold more moisture,

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resulting in higher extreme intensities when large-scale synoptic conditions do become favorable for precipitation (Christensen and Christensen 2003).

Modeling studies using global and/or regional climate models are often used to estimate the future change in extreme precipitation. Global circulation models (GCMs) are generally capable of simulating precipitation aggregated to the coarse grids on which they operate reasonably well, but tend to underestimate extreme precipitation (Sillmann et al. 2013a). Still, they are useful tools to predict future changes in extreme precipitation on a global scale (Sillmann et al. 2013b). However, the resolution of GCMs is too coarse to capture high impact storms with high local daily or hourly accumulations. To determine if and how much localized extreme precipitation events might change in the future for a given region, regional climate models (RCMs) are typically used to downscale GCM output. Due to advances in computational power, the resolution of these RCM simulations has been gradually increasing, and we are now at a point where kilometer scale climate simulations are feasible (Prein et al. 2015; Kendon et al. 2016). This advance is important, since at this scale, the sub-grid scale parameterization of deep convection is no longer necessary, as deep convection is sufficiently resolved by the model grid (Weisman et al. 1997). Removing the need for convective parameterization could improve RCM simulations considerably, since studies have shown they have several important deficiencies (Kendon et al. 2012; Langhans et al. 2013; Prein et al. 2013; Ban et al. 2014; Fosser et al. 2014; Brisson et al. 2016).

In recent years, the possible added value related to moving to convection permitting scale (CPS) has been investigated by a number of studies. Most studies have focused on precipitation, although a few have looked into possible benefits for other variables such as temperature (Prein et al. 2013; Ban et al. 2014; Brisson et al. 2016) and cloud cover (Brisson et al. 2016), or when modeling the impact of land use change scenarios, such as urbanization (Wouters et al. 2013; Trusilova et al. 2013) and deforestation (Vanden Broucke and Lipzig 2016). Improvements over nCPS were found for most of these variables and applications.

However, the main focus of research on regional climate modeling at CPS is still on precipitation. Several precipitation evaluation studies have been performed, comparing non convection-permitting scale (nCPS) to CPS simulations for different regions of the world (Prein et al. 2015; Kendon et al. 2016). Most of these studies agree that the largest benefits of CPS are to be found in the summer season, due to the fact that convective systems, which occur more frequently in summer, are now explicitly resolved. One of the most often reported improvements for summer is a shift in the diurnal cycle of precipitation, towards later in the afternoon, as well as an increase in the amplitude of the diurnal cycle (Ban et al. 2014; Fosser et al. 2014; Brisson et al. 2016). Both

changes bring the diurnal cycle closer to observations. Also, most studies agree that the explicit representation of convective systems at CPS vastly improves the distribution of precipitation on the hourly timescale during summer (Kendon et al. 2014; Chan et al. 2014b; Fosser et al. 2014; Ban et al. 2014, 2015; Brisson et al. 2016; Tabari et al. 2016). nCPS simulations tend to have too few intense hourly precipitation events, a bias that is largely alleviated at CPS. Finally, the spatial distribution of precipitation tends to improve due to the better resolved orography (Ban et al. 2014; Brisson et al. 2016).

The literature is less clear on the added value of CPS for the representation of precipitation at longer timescales (e.g. 6 hourly or daily precipitation accumulations) or for different seasons. For the daily timescale in summer, some studies report improvements similar to those found in hourly accumulations (Chan et al. 2013), while others find smaller improvements (Fosser et al. 2014), or no improvements (Ban et al. 2014; Brisson et al. 2016). The winter season, on the other hand, typically receives less attention than summer. Most studies that do present results for the winter season, however, conclude that, aside from a superior representation of the spatial distribution of precipitation over complex terrain, the added value of CPS in the winter season is significantly smaller than during summer (Chan et al. 2013; Prein et al. 2013; Fosser et al. 2014).

Another question that has received considerable attention in literature recently is whether there is a significant difference in the simulated future climate change signal of precipitation when moving from nCPS to CPS. Studies that address this question generally agree that future changes in main seasonal precipitation and precipitation frequency are robust across model resolution (Kendon et al. 2016). Concerning the future change in daily accumulation extremes during summer, some consensus can be found as well, with most studies reporting larger increases in the frequency of extreme precipitation events at CPS (Chan et al. 2014a; Ban et al. 2015; Saeed et al. 2017).

For hourly accumulations however, considerable disagreement exists. Only a handful of studies have compared the future climate change signal of extreme precipitation at this timescale, focusing mostly on summer. One study reports a significantly larger increase in extreme precipitation events on the hourly timescale at CPS (Kendon et al. 2014; Tabari et al. 2016). Others do not find any significant difference between CPS and nCPS (Fosser et al. 2017), or report mixed results with larger increases at CPS for only parts of the hourly rainfall intensity range (Chan et al. 2014a; Ban et al. 2015).

Of course, although these studies all address the same research question, the specific modeling setup employed does differ in a number of areas. These include the regional climate model used, future carbon emission scenario, time period (near future versus end of century), simulation length, domain size

and topographic complexity. Concerning the latter, while some of the studies mentioned above have been performed for regions that are predominantly flat, such as the southern part of the UK (Kendon et al. 2014; Chan et al. 2014a) or the Brussels area (Tabari et al. 2016), others have focused on regions with more complex topography, like south-west Germany (Fosser et al. 2017) or the Alps (Ban et al. 2015). Research has shown that in such regions, local thermally driven slope and valley circulations can influence and/or trigger convection (Langhans et al. 2013).

Considering the lack of consensus discussed above, more research on the added value of CPS in simulating the future change in extreme precipitation events on both the daily and hourly timescale is needed. Therefore, the main goal of this study is to add to the existing body of research on this topic. We do this by first performing a model evaluation, to assess the added value of CPS in simulating the frequency of extreme precipitation events in the present day. Next, we compare the end of century extreme precipitation climate change signal of simulations at nCPS (0.11° grid resolution) and CPS (0.025° resolution), using control and future simulations of 30 years in length, and for a relatively large model domain centered on Belgium. Besides the 30-year length of the simulations period (all but one existing study use 10 year simulations), an important novelty here is that the domain is comprised of both a relatively flat area (Flanders and the Brussels capital region in the north), as well as a region of moderate topography (the Ardennes low mountain range in the south). Therefore, separating these two regions in our analysis will allow us to determine whether the added value of CPS in simulating extreme precipitation depends on topographic complexity, as disagreement in existing literature appears to suggest.

## 2 Methods and materials

### 2.1 Model simulations

The regional climate model used in this study is COSMO-CLM. This model was originally developed by the German weather service for numerical weather prediction, and was

later adapted for use in climate simulations (Rockel et al. 2008). This study uses version 5.0, a unified version suitable for both numerical weather prediction and climate, released in 2015 and adapted as the recommended version in 2016. A full technical description of the model is available at <http://www.clm-community.eu>.

Two sets of regional climate model simulations are performed, one set at nCPS, the other at CPS (Table 1). All model simulations use the Runge–Kutta two level time-stepping scheme and the Ritter–Geleyn radiation scheme (Ritter and Geleyn 1992). All model simulations are performed using 40 vertical height levels.

The nCPS simulations use the internationally agreed upon CORDEX grid for Europe (Fig. 1a). This grid has a horizontal grid resolution of 0.11°, is 450 by 438 pixels in size and covers all of Europe as well as parts of North-Africa, the Middle-East and Russia. The simulations use a model timestep of 90 s. Moist convection is parameterized using the Tiedtke scheme (Tiedtke 1989).

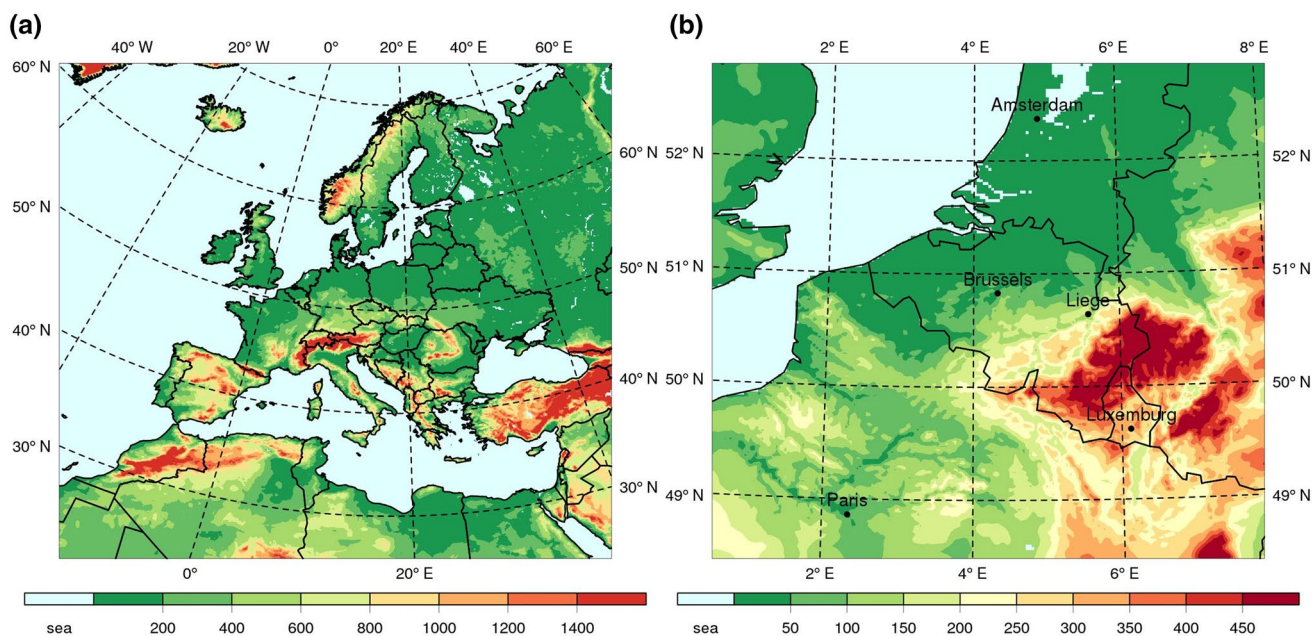
The CPS simulations are nested inside the nCPS simulations. The grid covers Belgium and surroundings, has a horizontal grid resolution of 0.025° and is 192 by 175 pixels in size (Fig. 1b). As recommended by Brisson et al. (2015) the CPS model domain is sizeable enough (538 by 490 km) to allow for a buffer zone of more than 100 km to each side of the analysis domain (Belgium), allowing enough space for convective system to develop. These simulations use a model timestep of 20 s. Note that shallow convection is still fully parameterized, since the horizontal resolution used is still insufficient to resolve it explicitly.

The CPS simulations use the urban land-surface scheme TERRA-URB, which was recently introduced to the COSMO-CLM model (Wouters et al. 2013; Trusilova et al. 2013, 2016; Demuzere et al. 2017). This surface scheme calculates radiation, heat and moisture fluxes between the urban environment and the atmosphere. It uses the semi-empirical urban canopy dependence parameterization SURY (Wouters et al. 2016), as well as an impervious water storage parameterization developed by Wouters et al. (2015). Anthropogenic heat emissions are included as an additional

**Table 1** Overview of model simulations performed for this study

Simulation-ID	Domain	Time period	Boundary conditions
EU-hindcast	EU [0.11°-450×438-nCPS]	1979–2014	ERA-INTERIM
> BE-hindcast	BE [0.025°-192–175-CPS]	1979–2014	ERA-INTERIM
EU-control	EU [0.11°-450×438-nCPS]	1975–2005	ECEARTH
> BE-control	BE [0.025°-192×175-CPS]	1975–2005	ECEARTH
EU-future	EU [0.11°-450×438-nCPS]	2069–2099	ECEARTH RCP8.5
> BE-future	BE [0.025°-192×175-CPS]	2069–2099	ECEARTH RCP8.5

This study uses a two-way nesting strategy: the 0.11° regional climate model simulations on a European domain are nested inside either ERA-INTERIM or EC-EARTH. In turn, the 0.025° regional climate model simulations on a Belgian domain are nested inside the 0.11° simulations



**Fig. 1** Overview of model domain size and topography, for our **a** nCPS (0.11°) and **b** CPS (0.025°) COSMO-CLM simulations

heat source to the first above-ground model layer, and are taken from seasonal and diurnal distribution functions (Flanner 2009). We opted to use TERRA-URB in our CPS simulations because comparisons with in-situ observations as well as satellite data show that when combined with a high-resolution modeling setup, TERRA-URB significantly improves simulated near-surface climate over European cities (e.g. 2 m temperature, humidity) and better represents the urban heat and urban dry island effects (Trusilova et al. 2013, 2016; Wouters et al. 2016; Varentsov et al. 2018). Also, intense radiation and eddy covariance flux measurements campaigns in the cities of Basel, Toulouse and Singapore have demonstrated that TERRA-URB also significantly improves the representation of all components of the surface energy budget (Wouters et al. 2015; Demuzere et al. 2017).

This study comprises both a model evaluation and an analysis of the future climate change signal. Hence, we perform hindcast runs driven by ERA-interim reanalysis data (0.75° resolution) as well as control and future runs driven by a GCM (1.125° resolution). The ERA-interim driven runs are 36 years in length, covering the time period 1979–2014. The GCM driven runs are 31 years in length, covering the time periods of 1975–2005 (control) and 2069–2099 (future). The first year of each simulation is considered as spin-up time and therefore discarded from the analysis.

The GCM used, EC-EARTH, is a state-of-the-art model developed collaboratively by 27 research institutions around Europe, and is part of the CMIP5 multi model ensemble used for the IPCC's fifth assessment report (Hazeleger et al. 2010, 2012). The realization chosen for downscaling in this study is

one of 16 recent EC-EARTH realizations performed using the emissions scenario RCP8.5, all using identical model settings but different initialization dates. This results in a certain amount of variability in the climate change signal in our region of interest (as shown in Supplements Fig. 14). The realization ultimately chosen for downscaling in this study is the realization with the most median future climate change signal out of these 16 members. In order to identify this member, a degree of extremeness score (Eq. 1) was calculated for each of them. In this equation,  $X_v$  is the variable of interest,  $\Delta X_{v,i}$  is the climate change signal of the  $i$ -th member,  $med_j \Delta X_{v,j}$  is the ensemble median of the climate change signal of  $X_v$ , and  $\frac{1}{n} \sum_j |\Delta X_{v,j}|$  is an estimate of the order of magnitude of the ensemble climate-change signal.

$$\sum_v \frac{|\Delta X_{v,i} - med_j \Delta X_{v,j}|}{\frac{1}{n} \left( \sum_j |\Delta X_{v,j}| \right)} \quad (1)$$

Equation 1: ensemble degree of extremeness score, calculated for each EC-EARTH ensemble member.

The variables taken into account when selecting the most median EC-EARTH member were seasonal mean temperature (for Belgium), seasonal mean precipitation (for Belgium and the whole of Europe separately) and seasonal mean sea level pressure differential in the latitudinal and meridional direction (for Belgium). An overview of these scores can be found in Supplements Fig. 14. Ultimately, the analysis identified member 1 as the most median member

within the RCP8.5 ensemble, so this member was chosen for downscaling.

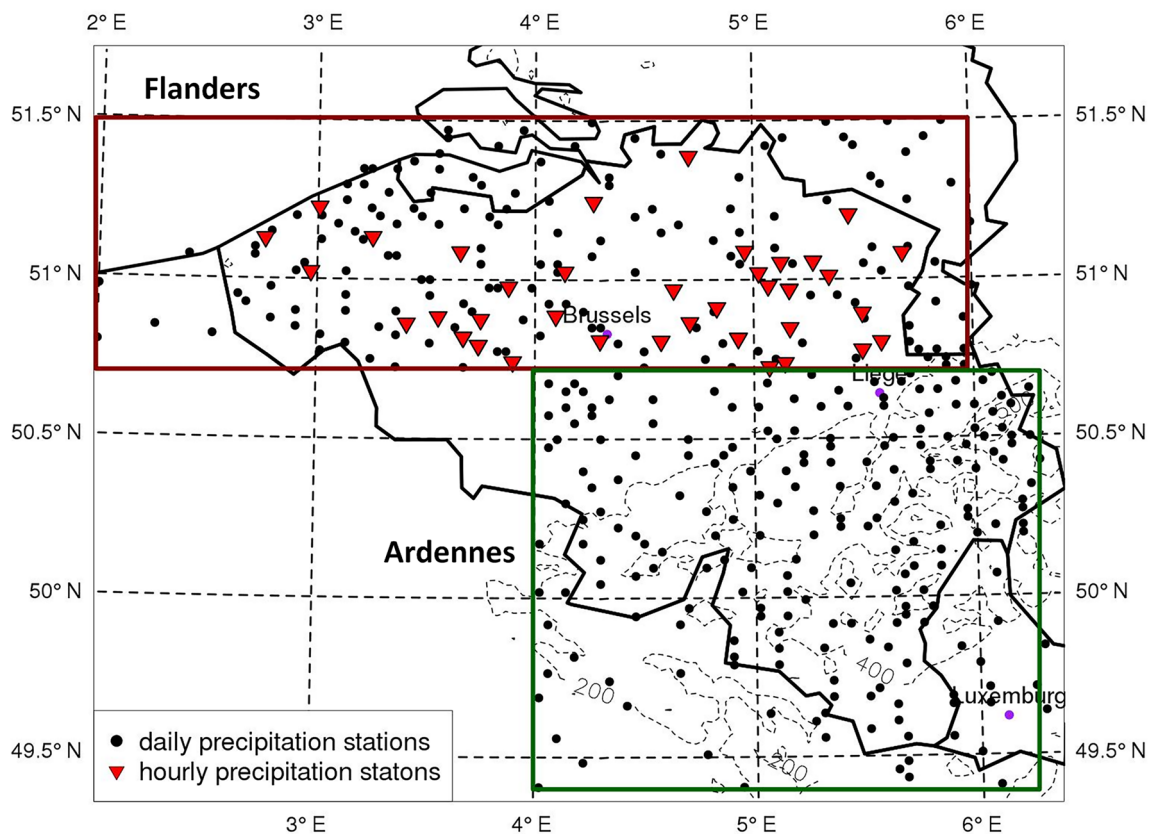
## 2.2 Observational data and analysis regions

Both daily and hourly precipitation accumulation observations were used for the evaluation portion of this study. The daily observations were derived from two datasets: one provided by the Belgian Royal Meteorological Institute (RMI), the other by the Global Historical Climatology Network-Daily (GHCN-D). From these datasets, the 163 daily precipitation stations which are located in our area of interest were retained for our analysis (Fig. 2). The resulting evaluation dataset covers a 30 year time period (1980–2009), and has an averaged temporal coverage of 59%. The hourly observations were derived from a dataset provided by the Flemish Environmental Agency (VMM). This datasets contains a total of 41 stations, covering a 12 year time period (2000–2011), with an averaged temporal coverage of 58%.

As mentioned in the introduction, our analysis focuses on two separate regions of interest: Flanders in the north and the Ardennes in the south (as shown by the red rectangles

in Fig. 2). Flanders is a heavily populated, relatively flat region and located close to the North Sea, while the more inland, relatively sparsely populated Ardennes region can be characterized as a low mountain range, with a maximum elevation of 694 m. These two regions differ significantly with regards to precipitation. Mean annual precipitation is 800 mm for Flanders, whereas for the Ardennes region, annual precipitation varies from 800 mm per year for the relatively flat northern part of the region up to 1500 mm per year for the topographic peaks in the east and southwest of the region. The main process responsible for this difference is an increase in stratiform precipitation over the Ardennes orography due to orographic uplift. However, observations show that convective activity is also responsible for part of the difference in mean precipitation, as the number of hours of thunderstorms is observed to be about 50% higher over the Ardennes' topographic peaks.

Finally, note that we only have hourly observational data for Flanders, and not for the Ardennes. Hence, the evaluation of precipitation extremes on the hourly timescale will be performed for Flanders only, while all other analysis will be performed for both regions.



**Fig. 2** Location of daily and hourly precipitation stations used for model evaluation. Also shown are domain topography (dashed lines) and the model analysis domains: Flanders (red rectangle) and Ardennes (green rectangle)

### 2.3 Extreme precipitation metric

As noted by Schär et al. (2016), careful consideration should be given to the type of metric used to describe future changes in extreme precipitation. Three methodologies are commonly used in literature: wet-day percentiles, all-day percentiles and threshold based methods. The first methodology, wet-day percentiles, starts by discarding all days or hours below a certain threshold, usually 1 mm/day or 0.1 mm/hour. Next, the relative change in the value of one or multiple precipitation percentiles towards the tail of the distribution is calculated (e.g. the 95th and 99th percentile of wet days, or  $P95_{\text{wet}}$  and  $P99_{\text{wet}}$ ), and used as a metric to describe the change in extreme precipitation.

Although the use of wet-day percentiles is very common in climate change studies, Schär et al. (2016) recommend against their use in studies that focus on extreme precipitation events. The reason being is that unlike all-day percentiles and threshold based methods, they are sensitive to changes in rainfall occurrence as well as intensity. For example, suppose we compare two future simulations, A and B that have the exact same intensities for their 10% highest precipitation days (e.g. largest event is 95 mm/day, second largest event is 92 mm/day, etc.). Simulation B, however, has a significantly higher increase in the total fraction of dry days. In this scenario, extreme percentiles calculated for wet-days only (e.g.  $P99_{\text{wet}}$ ) will be higher for simulation B. Therefore, this could possibly lead to the erroneous conclusion that extreme precipitation increases more in simulation B, despite the fact that they have an identical incidence of extreme events.

In this study, we opt to use a frequency method based on thresholds, which avoids this pitfall. The threshold values (absolute values expressed in mm/day or mm/hour) are percentiles calculated for a reference time series that includes both dry and wet days, and are then kept fixed for the subsequent analysis. For example, for the extreme precipitation climate change part of this study, we calculate a range of percentile values using the present-day CPS simulation precipitation time series as reference, from P95 to P99.999. The corresponding mm/day values are then fixed (e.g. 15 mm/day for P95, 22 mm/day for P98, etc.), and used in plots showing the relative increase in number of events exceeding these thresholds for both the nCPS and CPS simulations. A similar approach is used for the model evaluation part of this study but here, the observations are used as the reference time series.

Note that when comparing the future change signal of nCPS and CPS simulations, we opt to compare the relative rather than absolute increase in the number of extreme precipitation events. This improves comparability with other studies that have looked into this topic (e.g. Chan et al. 2014a; Kendon et al. 2014; Ban et al. 2015; Tabari et al.

2016; Fosser et al. 2017), which predominantly compare the relative increase. Also, it allows us to optimally compare the scalability of extreme precipitation in both setups, despite the fact that they may differ in the number of extreme events simulated for the present day.

To test the significance of (1) the difference in observed and modeled extreme precipitation, (2) the future change signal and (3) the difference in the future change signal between nCPS and CPS simulations, a bootstrap resampling methodology is used, i.e., for each timeseries, 1000 alternatives are generated which are randomly resampled from the original timeseries, allowing for 1000 estimates of the number of events exceeding various thresholds. Next, a student t.test (significance level 0.01) is performed to determine whether the mean number of threshold exceedances differs between model and observations, future and present or nCPS and CPS. For the spatial plots, a different method is used, namely Pearson's Chi square test of independence (significance level 0.1).

## 3 Results

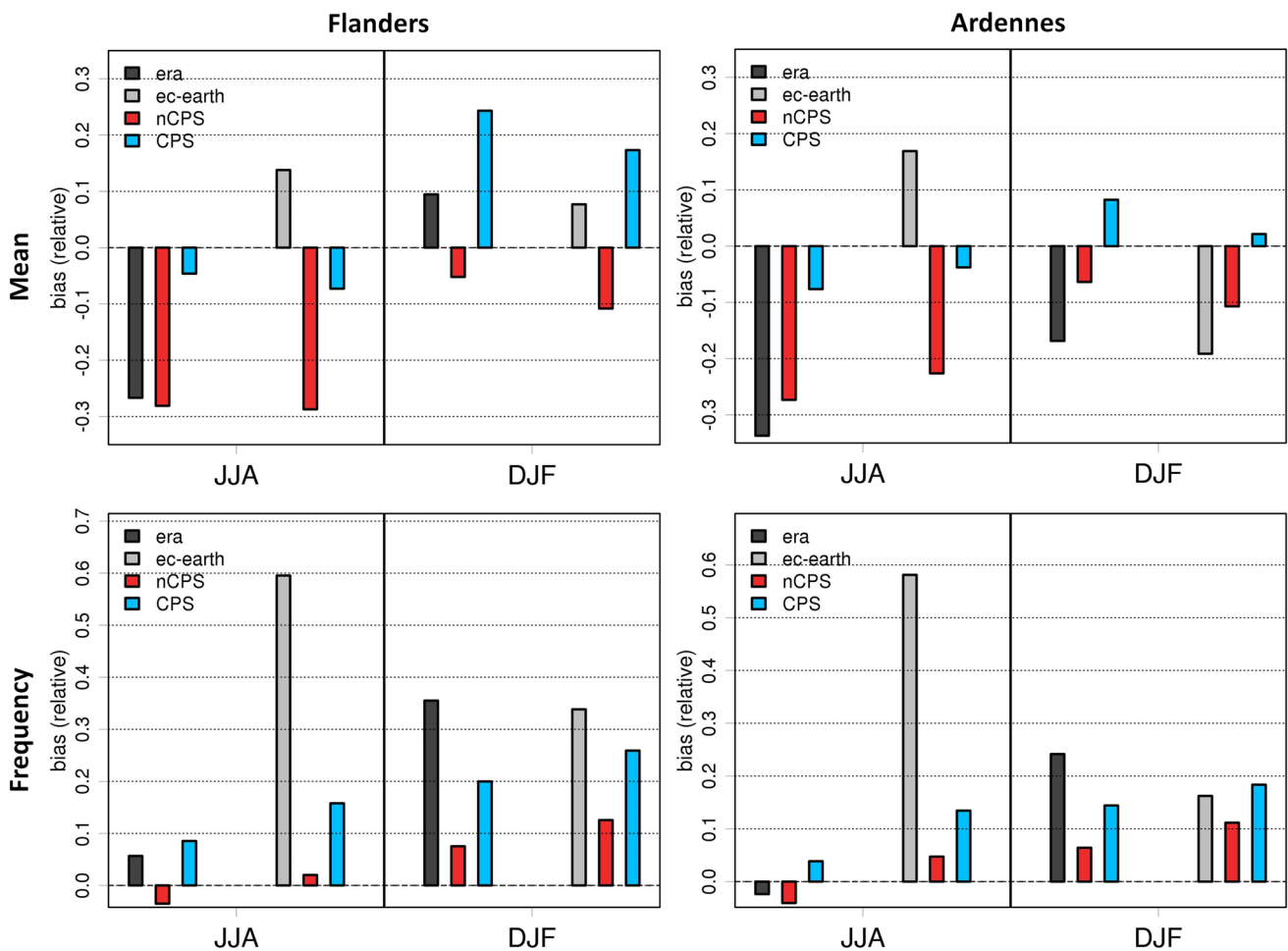
As mentioned in the introduction, this section comprises of both a model evaluation (section “[Model evaluation](#)”) and an analysis of the future climate change signal (section “[Future climate](#)”). Both sections briefly discuss mean precipitation, before moving on to the focus of this study, which is extreme precipitation.

### 3.1 Model evaluation

#### 3.1.1 Mean precipitation and precipitation frequency

As shown in Fig. 3, our nCPS simulations tend to underestimate mean summer precipitation in both analysis regions, whereas our CPS simulations overestimate mean winter precipitation, especially in Flanders. Interestingly, these biases do not differ much between the ERA-interim and EC-EARTH driven runs, despite the fact that these two sets of forcing data are characterized by significantly different precipitation biases of their own. Hence, in these simulations, the RCM mean precipitation bias seems to be largely independent of the precipitation bias in the forcing data, for nCPS and CPS simulations alike.

For precipitation frequency, defined as the fraction of days with precipitation exceeding 1 mm, the model bias does not seem to differ much between regions. The nCPS frequency bias is always smaller than CPS, with the latter overestimating precipitation frequency in every season, but more so in winter. However, both nCPS and CPS model biases are small compared to the driving data, especially for



**Fig. 3** Relative model mean precipitation bias and precipitation frequency bias (fraction of days with precipitation > 1 mm), for Flanders and Ardennes. Bias is calculated as modeled values minus observations, divided by observations. Bias is shown for driving data (era and ec-earth) and COSMO-CLM runs regridded to the driving data

grid. The red and blue bars next to the black era bar show the bias for the COSMO-CLM runs driven by ERA-INTERIM, while the red and blue bars next to the grey ec-earth bar show the bias for the COSMO-CLM runs driven by EC-EARTH

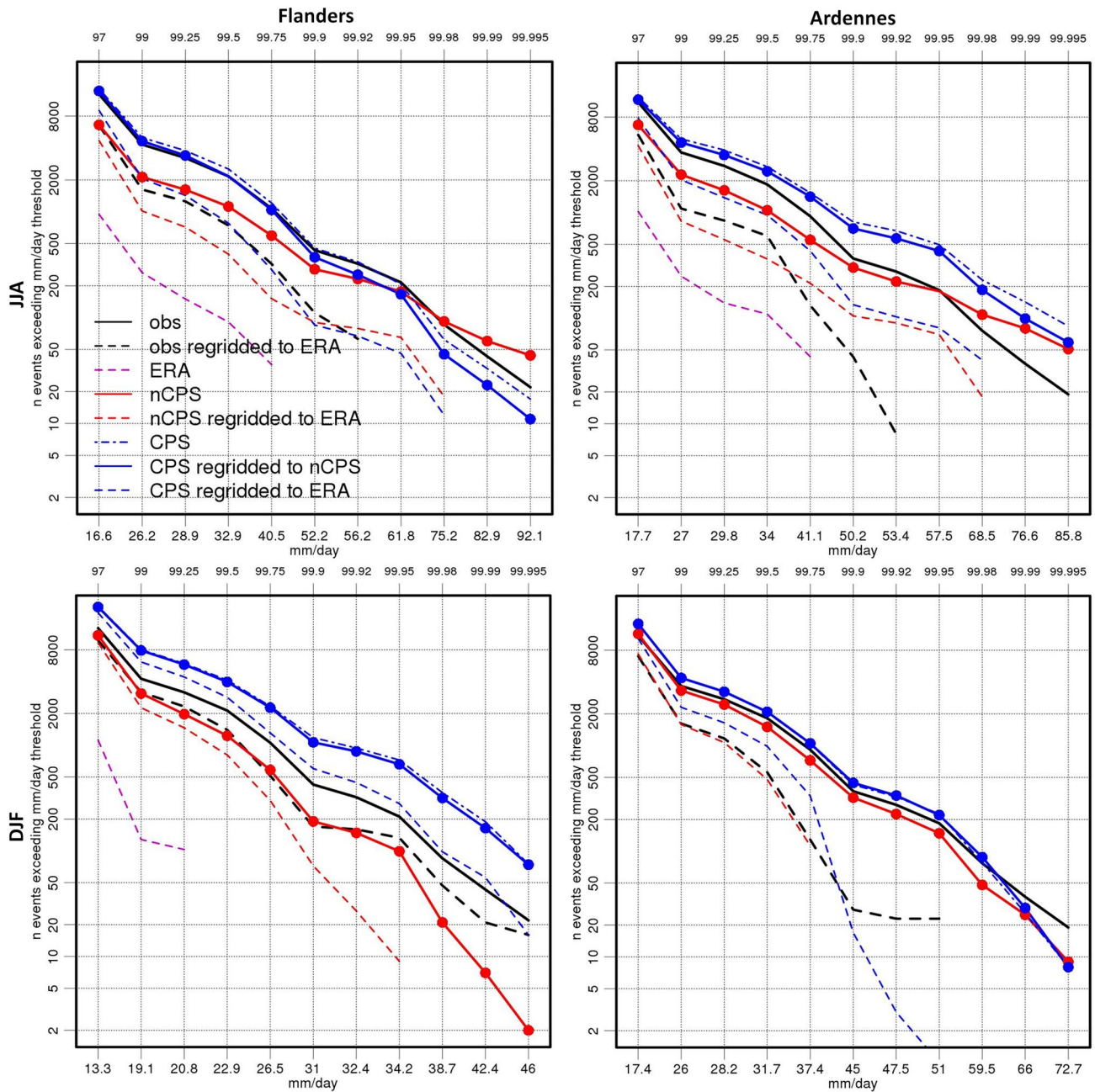
the EC-EARTH driven runs, showing the benefit of dynamically downscaling re-analysis or GCM data with an RCM.

### 3.1.2 Extreme precipitation on the daily and hourly timescale

The ERA-interim re-analysis (Fig. 4) and EC-EARTH GCM simulations (not shown) both strongly underestimate the occurrence of extreme daily precipitation accumulation events. Downscaling to nCPS and CPS scale increases the number of extreme daily events, but with large differences between the two model setups depending on season, region and intensity (Fig. 4). The biggest difference between the two is that CPS tends to produce more extreme events than nCPS, which is true for all but two combinations: the Ardennes during winter (Fig. 4 and Supplements Fig. 15) and the most extreme events (60–100 mm/day) in Flanders

during summer. However, this increase in the occurrence of extreme events does not mean that CPS is more in line with observations, e.g., the increase leads to better correspondence with observations in Flanders during summer (for the first part of the intensity range), but leads to a strong overestimation in Flanders during winter. Thus, overall, we can conclude that on the daily timescale, CPS simulations are not necessarily superior to nCPS in simulating the frequency of extreme precipitation events.

An area where CPS is clearly superior to nCPS, however, is in simulating the occurrence of hourly precipitation extremes. CPS simulates a higher number of events than nCPS throughout the hourly intensity range (Fig. 5, Supplements Fig. 16 and Supplements Fig. 17) and as a result, is closer to observations (Fig. 5). The improvement over nCPS is largest when the chance of an intense convective event is at its peak (i.e., in summer and for daytime). It is



**Fig. 4** Number of events exceeding various daily precipitation thresholds, for observations and model runs. For the nCPS and CPS runs, a circle is drawn when the difference between model and observations is statistically significant ( $t$  test,  $p < 0.01$ ). The thresholds used are

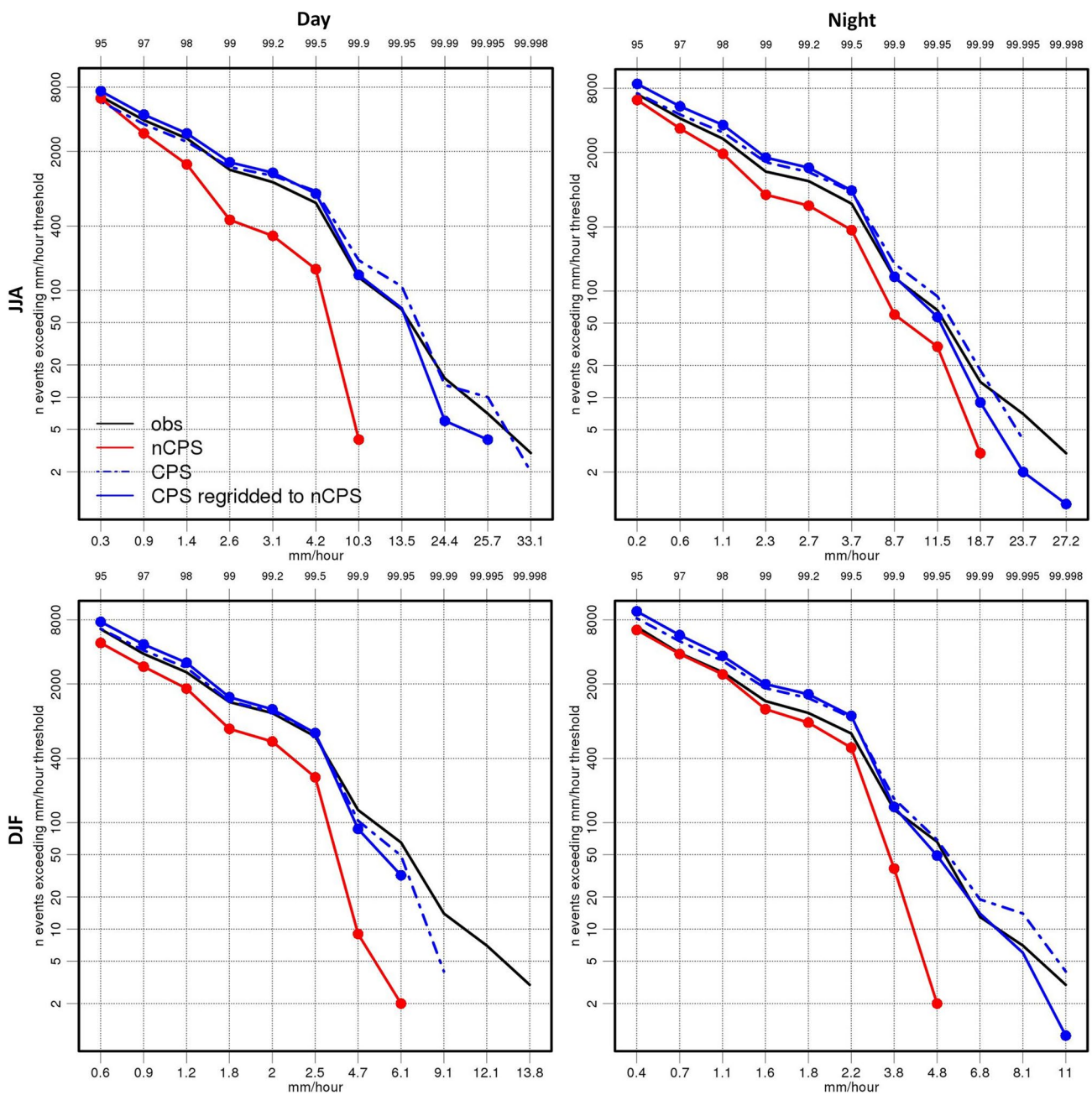
also not merely the result of the increase in resolution, as the CPS simulations are still clearly superior when aggregated to the nCPS grid. Therefore, the improvement can be linked to a better representation of the dynamics of convective systems, owing to the move from parameterized to explicit convection.

The improvement in extreme hourly events when going from nCPS to CPS is smaller in winter, but still present. Other

daily precipitation percentiles calculated on the observational time-series. Shown on the top x-axis of each figure are the percentile values used (e.g. 97th, 98th, etc.)

studies that report a similar wintertime improvement link it to a better resolved orography at CPS, which leads to a better representation of orographic forcing (Ikeda et al. 2010; Rasmussen et al. 2011). In this study however, the improvement is surprising, since Flanders is largely flat, with only small topographical features. However, just like summer, it can probably be linked to convective storms. Although precipitation in winter is dominated by large-scale stratiform systems,





**Fig. 5** Number of events exceeding various hourly precipitation thresholds, for observations and model runs, for daytime (12–20 UTC) and nighttime (0–8 UTC), for Flanders only. For the nCPS and

CPS runs, a circle is drawn when the difference between model and observations is statistically significant (t test,  $p < 0.01$ ). Shown on the top x-axis of each figure are the percentile values used

on occasion, convective storms can and do occur, with a frequency that is about 1/20th of that in summer (Goudenhoofd and Delobbe 2012). Wintertime storms are smaller than summertime storms in terms of both mean volume and mass. They also have a considerably lower cloud top height, which is the variable most closely linked to storm intensity (Goudenhoofd and Delobbe 2012). This decrease in convective storm frequency and intensity explains why improvements at CPS are smaller during wintertime, but still present.

As previously mentioned, we do not have hourly evaluation data for the Ardennes region. However, a comparison of just the model data did show that the difference between nCPS and CPS in this region is similar to Flanders, as nCPS has fewer extreme events for all season and time of day combinations (Supplements Fig. 16 and Supplements Fig. 17). One notable difference from Flanders is that the difference in number of extreme winter events, while still present, is significantly smaller. This is likely due to the fact that there

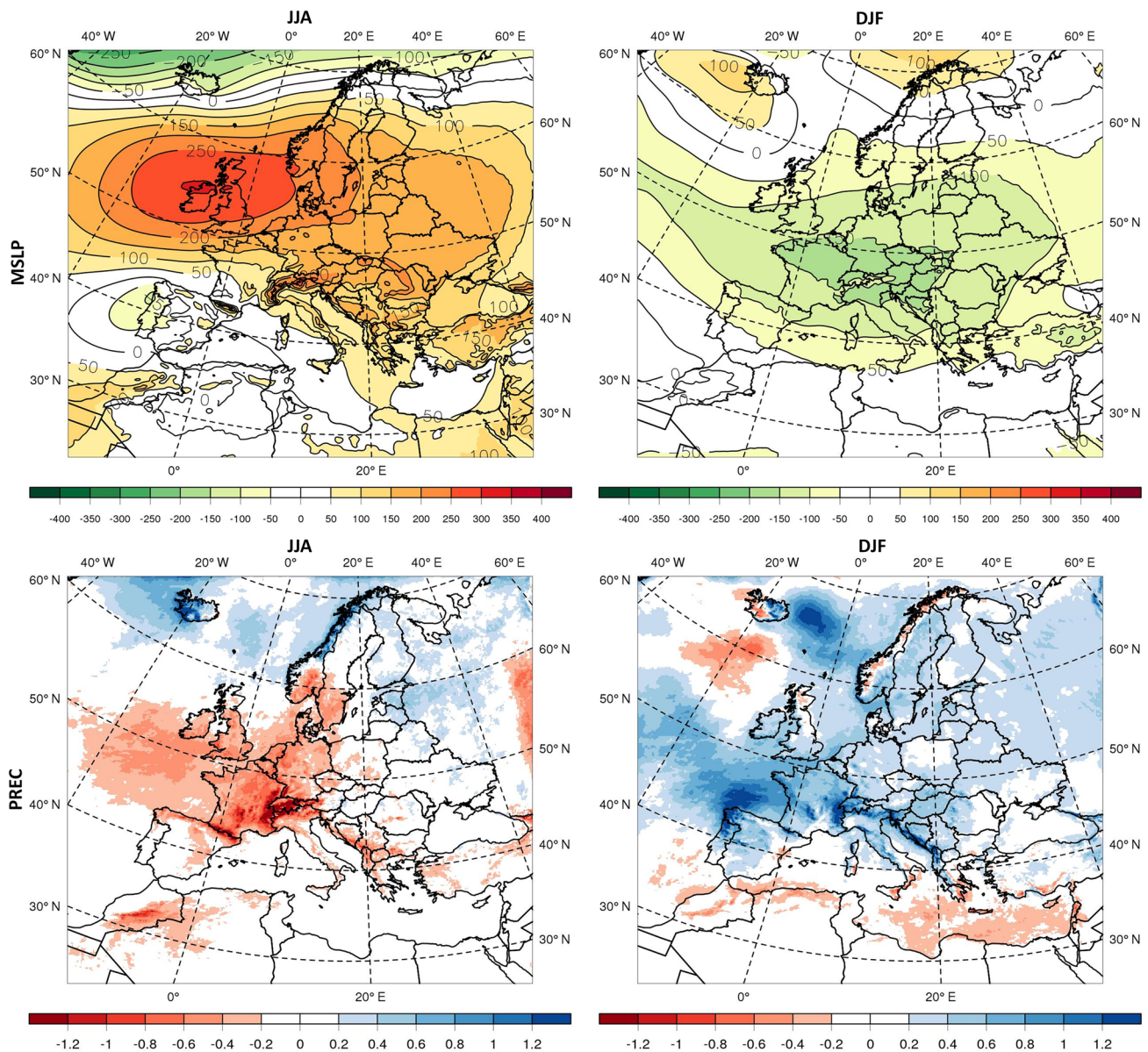
is less wintertime convective activity over the Ardennes region, as wintertime extreme precipitation in this region is predominantly linked to orography rather than convection. We will discuss this observation further in section “[Model Evaluation](#)”.

## 3.2 Future climate

### 3.2.1 Change in large-scale circulation and mean precipitation

The EC-EARTH member used in the downscaling process of this study is characterized by significant future changes

in large-scale circulation over Europe. These changes are of course inherited in our RCM runs and, for a large part, determine the change in future precipitation frequency as well as future mean precipitation. Summer is characterized by an increase in mean sea level pressure over the British Isles, increasing the occurrence of easterly flow over much of Western Europe, which brings in relatively dry continental air (Fig. 6). As a result, summer precipitation frequency and summer mean precipitation decrease, with the largest absolute decreases over the Alps and Pyrenees mountains. For our study area, Belgium, the EC-EARTH GCM runs simulate a decrease in precipitation frequency (% of days with precipitation > 1 mm) of about 30%, and a decrease of



**Fig. 6** Maps of absolute future change (2070–2100 minus 1980–2010) in mean sea level pressure (MSLP, in hPa) and daily mean precipitation (PREC, in mm) for Europe, as simulated by the nCPS runs

mean summer precipitation of about 25%. Both nCPS and CPS runs, nested inside the EC-EARTH runs, enhance this drying for the Belgian region (Fig. 7). Differences in the degree of drying between the two setups range from 1 to 5%, and are statistically significant (t-test,  $p < 0.05$ ), except for the difference between nCPS and CPS in Flanders in summer (t-test,  $p = 0.061$ ).

Winter, in contrast, is characterized by a mean wetting signal. The reason for this wetting is a decrease in mean sea level pressure centered on continental Europe, increasing the incidence of westerlies that bring in relatively warm, moist air from the Atlantic (Fig. 6). This wetting affects most of Western-Europe, with the largest increases seen near the western coastlines of Spain and France. For Belgium specifically, precipitation frequency increases by 2–11%, while the increase in mean precipitation amounts to 17–25%, depending on simulation and sub-region (Fig. 7). The latter is larger than the former because it is not only determined by changes in precipitation frequency, but also by changes in precipitation intensity. With the future atmosphere being warmer and therefore able to hold more moisture, future precipitation events become more intense. This is also true for summer but here, the effect of more intense local storms on mean precipitation acts against the mean drying signal.

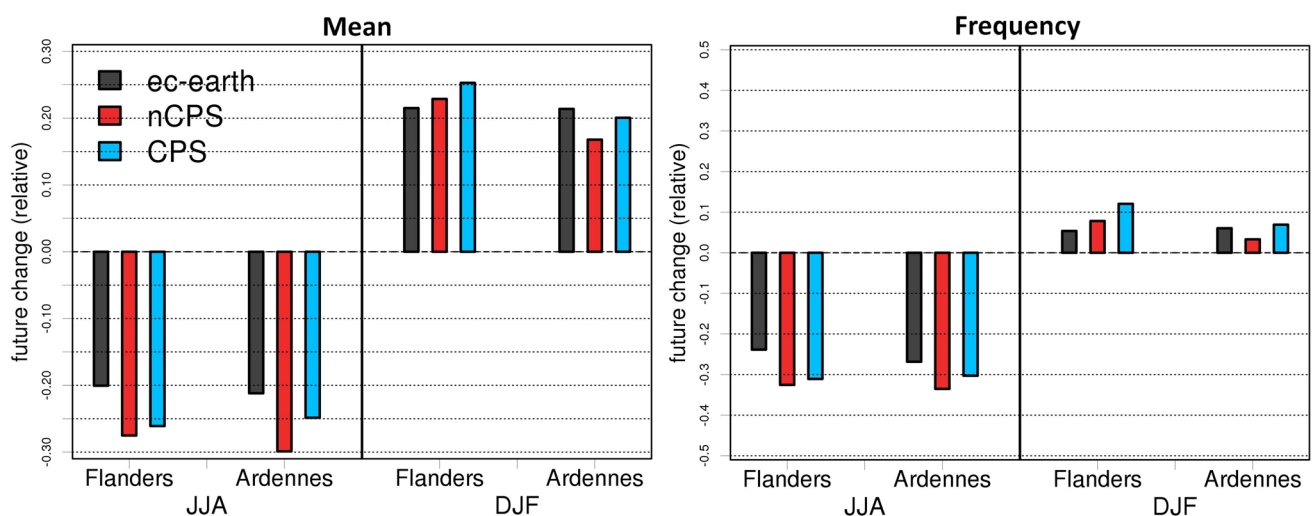
### 3.2.2 Change in extreme precipitation on the daily timescale

Figure 8 shows the relative future change in the number of times various daily precipitation thresholds are exceeded. In summer, events of medium intensity will occur less often,

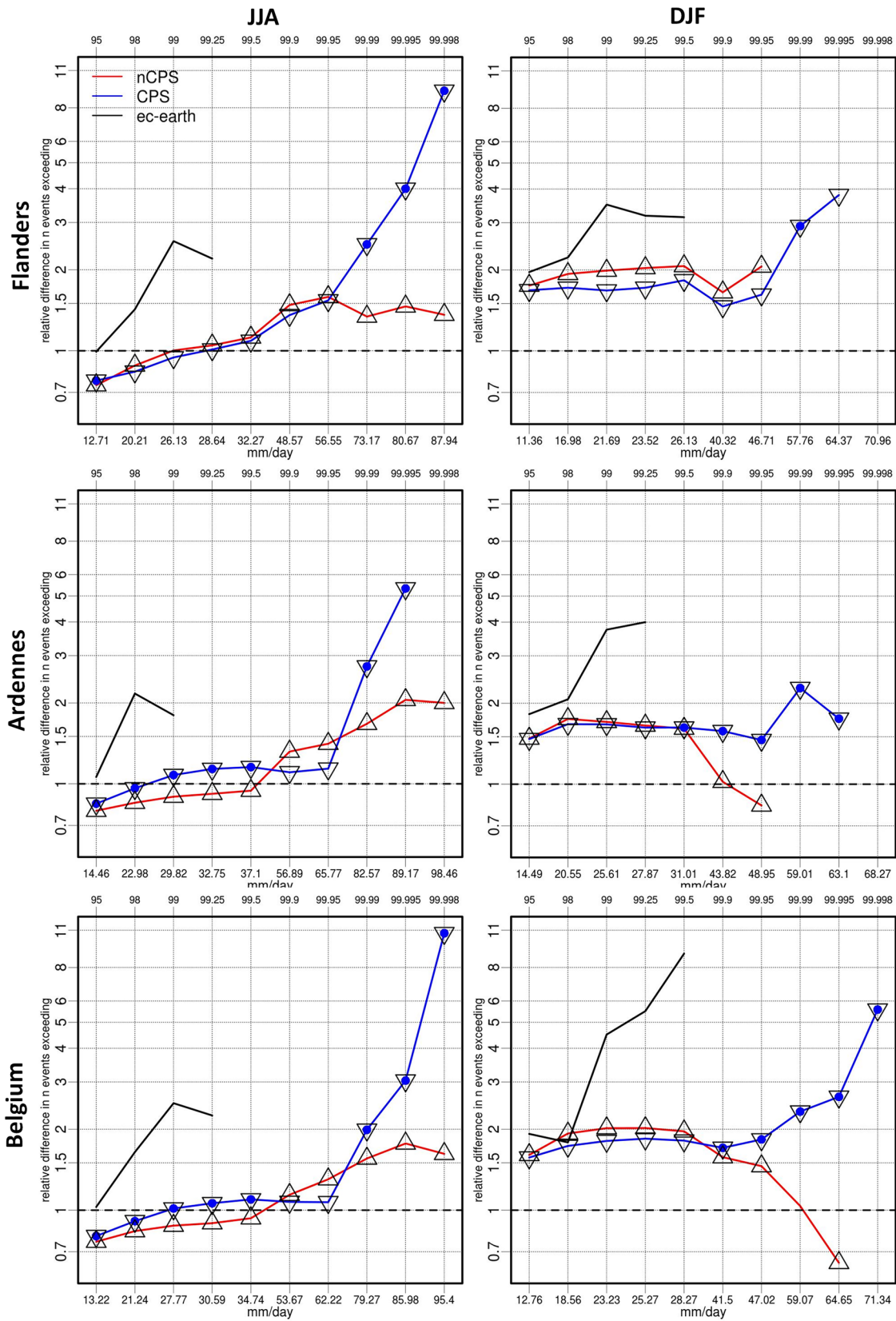
as expected from the drop in daily precipitation frequency associated with a higher occurrence of easterly flow. At the same time, the increased energy and moisture availability when weather conditions are in fact favorable for convective storm development (e.g., low pressure system over Belgium, or flow coming from south-west to north) means that the storms that do occur have a higher mean intensity. As a result, there is an increase in the number of times that extreme thresholds are exceeded in the future. This summer season pattern is present in both nCPS and CPS simulations, but is more pronounced at CPS, which has a significantly lower decrease in the number of medium intensity daily accumulation events, as well as a significantly higher increase in the number of very extreme events.

In winter, nCPS and CPS show a similar increase in the number of extreme daily accumulation events for most of the intensity range, but again, show significantly contrasting signals for the most extreme events. At CPS, the most extreme events increase even more than events of medium intensity while at nCPS, they increase less or even decrease. It is worth noting though, that the intensities at which the nCPS and CPS climate change signals diverge are very rare, and while their present-day occurrence is underestimated at nCPS, it is overestimated at CPS (as shown in section “Model evaluation”).

The differences between nCPS and CPS just discussed do not differ much between regions, as they are quite similar for Flanders, Ardennes and Belgium as a whole. We can therefore conclude that, at least in these simulations, the difference and possible added value of CPS in modeling the future change in extreme precipitation on the daily timescale does not depend on topographic complexity. To confirm this, the relative change in the number of events exceeding certain



**Fig. 7** Relative future change ( $[\text{future-present}]/\text{present}$ ) in mean precipitation (left panel) and precipitation frequency (right panel, frequency defined as percentage of days with precipitation  $> 1$  mm) for EC-EARTH, nCPS and CPS, for the analysis regions of Flanders and Ardennes



**Fig. 8** Relative future change (future/present) in number of events exceeding various daily precipitation thresholds. The CPS precipitation field was regridded to the nCPS grid before calculating these statistics. A triangle (nCPS) or reverse triangle (CPS) is drawn if the relative future change is statistically significant (t test,  $p < 0.05$ ). A blue circle is drawn when the relative change in number of events is significantly higher (t test,  $p < 0.01$ ) at CPS than at nCPS. A red circle is drawn when the reverse is true. The thresholds used are daily precipitation percentiles calculated on the CPS control run. Shown on the top x-axis of each figure are the percentile values used

daily accumulation thresholds were mapped for both summer (Fig. 9) and winter (Supplements Fig. 18). No clear link to orography can be distinguished in either summer or winter. Instead, the spatial pattern appears to be random, reflecting the natural variability inherent in our model simulations.

### 3.2.3 Change in extreme precipitation on the hourly timescale

In contrast to extreme daily events, both the extreme hourly precipitation climate change signal itself as well as the difference between nCPS and CPS show a regional dependency (Figs. 10, 11). In summer (Fig. 10), CPS simulations project an increase in extreme hourly precipitation events in both Flanders and Ardennes. The magnitude of this increase depends on intensity, with the extreme intensity events increasing more than those of medium intensity. Our nCPS simulations are able to replicate this climate change signal in the Ardennes, but not in Flanders. For Flanders, nCPS simulations generally project a decrease in the amount of extreme precipitation events during daytime, and project a significantly lower increase during nighttime.

Maps of the relative change in number of extreme hourly precipitation events for a number of thresholds show that for daytime (Fig. 12), this regional difference is clearly linked to the topography of our study area. In both nCPS and CPS simulations, the area coinciding with the Ardennes low mountain range is characterized by higher, significant increases in extreme hourly precipitation. Also, they show that nCPS and CPS disagree over changes in the flatlands areas outside of the Ardennes, like Flanders, where nCPS generally projects a decrease, whereas CPS project no change. For nighttime the link to topography is less clear. The spatial pattern of the increase in extreme precipitation is similar in both model setups, with the highest increases seen in the middle of the domain, over an area that is largely flat (Fig. 13). The location of this area does not appear to be linked to a particular geographic triggering feature, like orography or a coastline. Although the area is present in both nCPS and CPS simulations, it is larger in size and intensity at CPS. In contrast, extreme precipitation changes in the Ardennes region are similar,

with both simulations setups projecting only small changes for these particular thresholds.

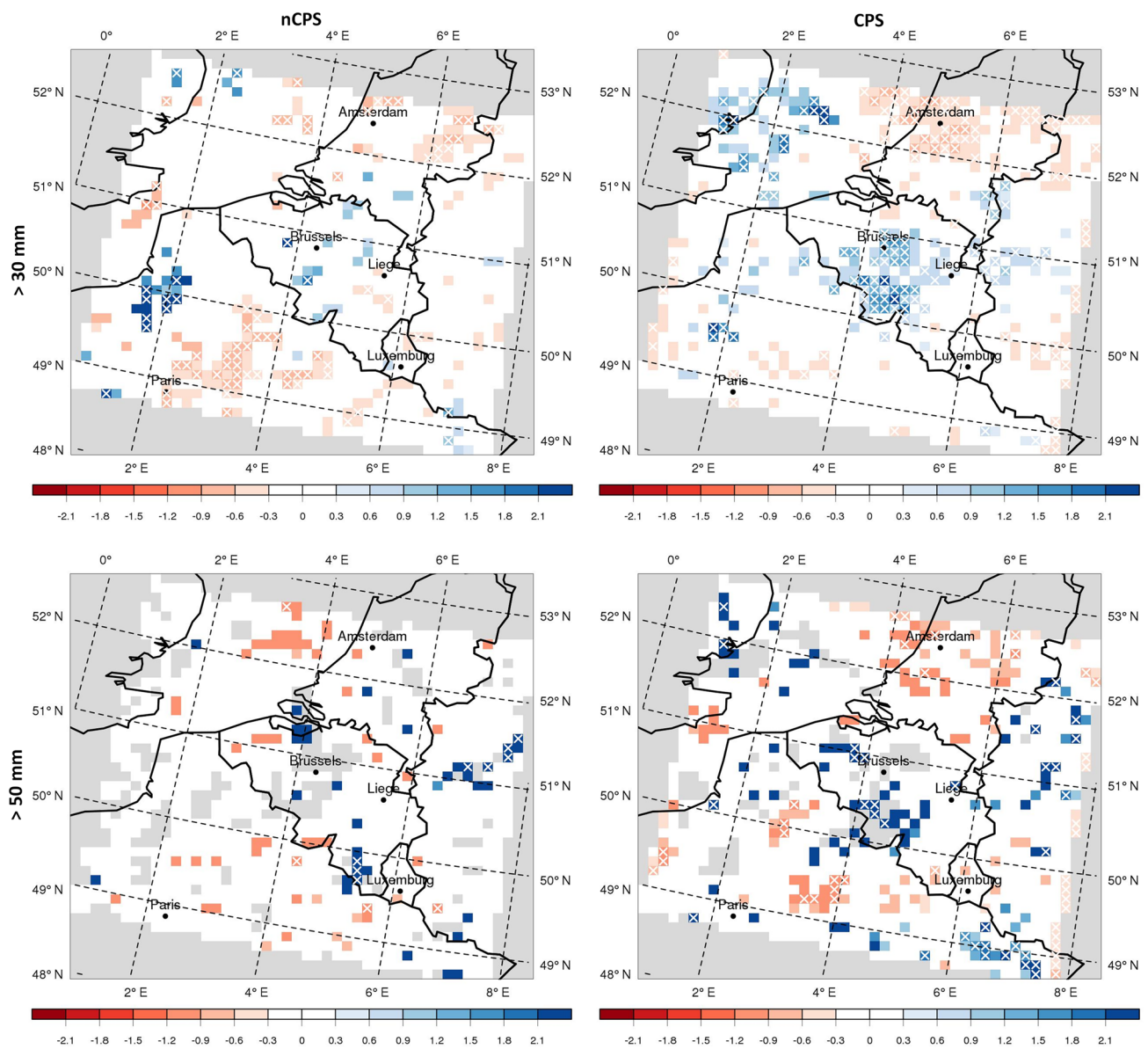
During wintertime, hourly extreme precipitation events of all intensity become more frequent, with the increase being higher for more extreme events (Fig. 11). This increase does not seem to be regionally dependent, as its magnitude is similar for the Flanders and Ardennes regions. There are, however, some differences between nCPS and CPS model setups. Most notably, during daytime, the frequency of extreme hourly events increases more at nCPS. It is worth noting though, that these nCPS simulations considerably underestimate the number of present-day extreme events (section “[Model evaluation](#)”). Therefore, higher relative increases in the number of extreme events can be obtained with absolute increases similar or even lower than those at CPS. It is therefore unlikely that the higher relative increases during daytime are linked to a difference in the physical mechanisms responsible for wintertime extremes. Finally, the spatial patterns of hourly extreme precipitation change in winter are very similar for both model setups (Supplements Fig. 19 and Supplements Fig. 20). There are no clear links to domain topography, as extreme precipitation does not seem to increase more over the Ardennes.

## 4 Discussion

### 4.1 Evaluation

Extreme precipitation evaluation results were presented for both the daily and hourly timescale (section “[Model evaluation](#)”). On the hourly timescale, the added value of CPS is clear-cut. Here, our results show that moving from nCPS to CPS increases the number of extreme hourly precipitation events, bringing modeled extreme precipitation more in line with observations. These results are in line with most existing literature on the subject (Chan et al. 2013, 2014b; Ban et al. 2014, 2015; Fosser et al. 2014; Kendon et al. 2014, 2016; Brisson et al. 2016). They highlight an important shortcoming in nCPS simulations and their associated convection-parameterization schemes. Namely, while these schemes appear to generate reasonable precipitation statistics at seasonal to daily timescales, they largely fail to capture statistics at the sub-daily scale in seasons and areas where convective precipitation is an important contributor to total precipitation. CPS simulations improve sub-daily statistics considerably, due to a better representation of the physical processes associated with convection.

On the other hand, on the daily timescale, the added value of CPS is less obvious. Our results show that moving from nCPS to CPS generally increases the number of times extreme precipitation thresholds are exceeded. Also, an increase is seen in both the summer and winter



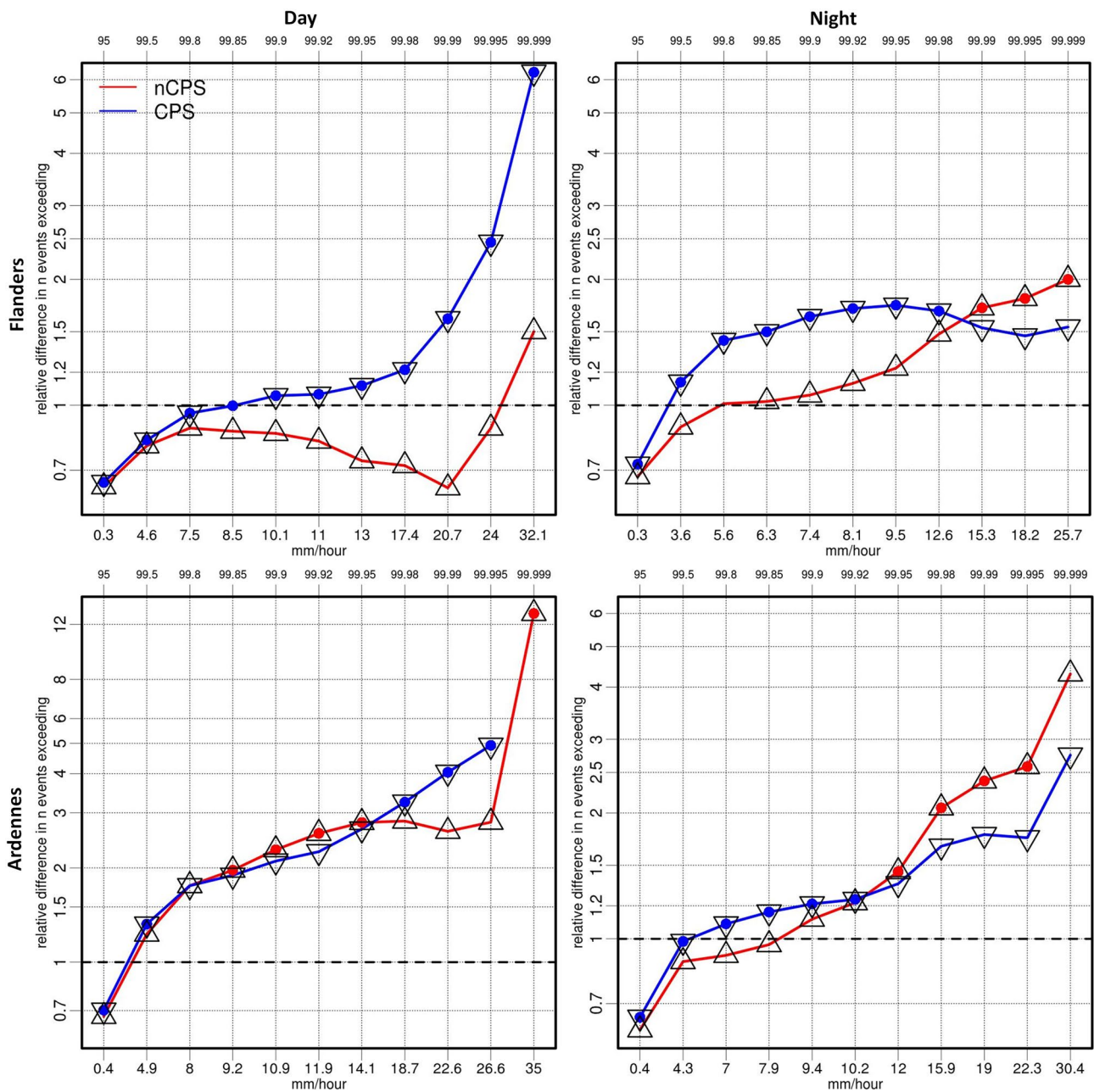
**Fig. 9** Maps of relative future change ( $[\text{future-present}]/\text{present}$ ) in number of events exceeding 30 mm/day (top panels) and 50 mm/day (bottom panels), for nCPS (left panels) and CPS (right panels), for summer. CPS values were regridded to the nCPS grid. Only pixels for which the change is significant on the  $p < 0.25$  level (Chi square test)

are colored. A white asterisk is drawn for pixels for which the change is statistically significant on the 0.1 level. Pixels for which there are no events exceeding these thresholds for the present-day period are drawn in grey

season, although the increase in winter is smaller. This result is largely consistent with existing literature that evaluates present-day extreme precipitation at both nCPS and CPS (Table 2), as almost all studies report more extreme precipitation at CPS as well. Where literature disagrees however, is whether this increase in extremes constitutes an improvement in model performance. In some studies, the increase brings modeled extreme precipitation more in line with observations (Ban et al. 2014, 2015), while for others, the increase leads to a significant

overestimation (Chan et al. 2013, 2014b; Fosser et al. 2014) or an improvement for only part of the daily intensity range (Brisson et al. 2016).

We hypothesize that CPS simulations are prone to overestimate the occurrence of extreme daily precipitation events due to the fact that, while the resolution employed in most CPS simulations is sufficient to realistically capture and resolve most convective events, small convective cores are still under resolved. Without a convection parameterization scheme to account for under resolved sub-grid scale



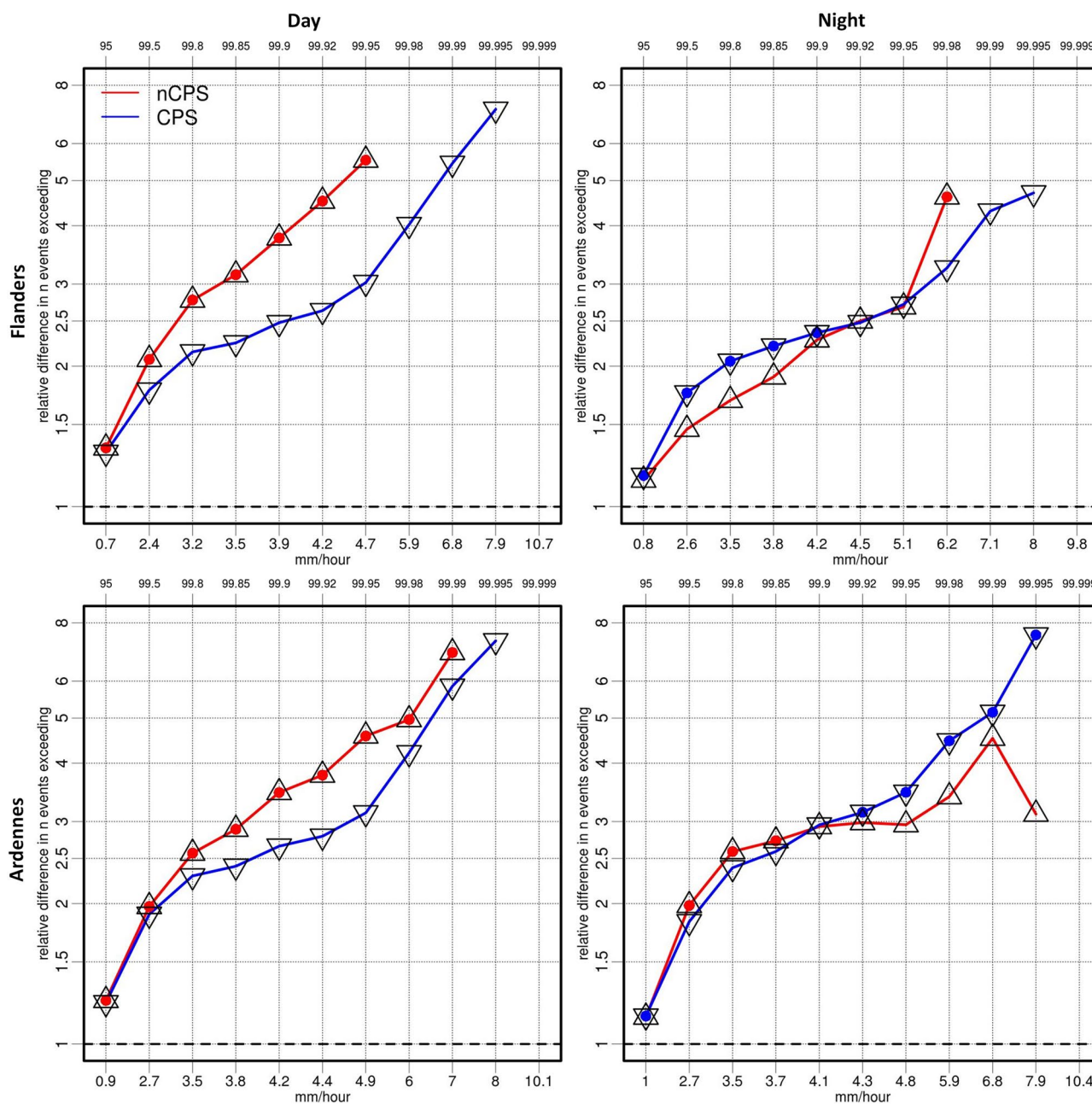
**Fig. 10** Relative future change (future/present) in number of events exceeding various hourly precipitation thresholds during summer (JJA), for Flanders (top panels) and Ardennes (bottom panels), for daytime (12–20 UTC) and nighttime (0–8 UTC). The CPS precipitation field was regridded to the nCPS grid before calculating these statistics. A triangle (nCPS) or reverse triangle (CPS) is drawn if the relative future change is statistically significant (t test,  $p < 0.01$ ). A

blue circle is drawn when the relative change in number of events is significantly higher (t test,  $p < 0.01$ ) at CPS than at nCPS. A red circle is drawn when the reverse is true. The thresholds used are hourly precipitation percentiles calculated on the CPS control run. Shown on the top x-axis of each figure are the percentile values used (e.g. 97th, 98th, etc.)

convection, the up and down drafts associated with these small cores have to occur at the grid scale used in the CPS simulation, possibly resulting in an overestimation of their associated precipitation intensity. If this hypothesis is true, increases and associated overestimations of the number of extreme precipitation events at CPS can be expected to be

largest in summer, when the conditions most favor the development of convective thunderstorms.

As mentioned in section “Model evaluation”, convective thunderstorms can occur in winter as well, albeit with a reduced frequency and intensity (Goudenhoofd and Delobbe 2012). Our results reflect this, as our CPS



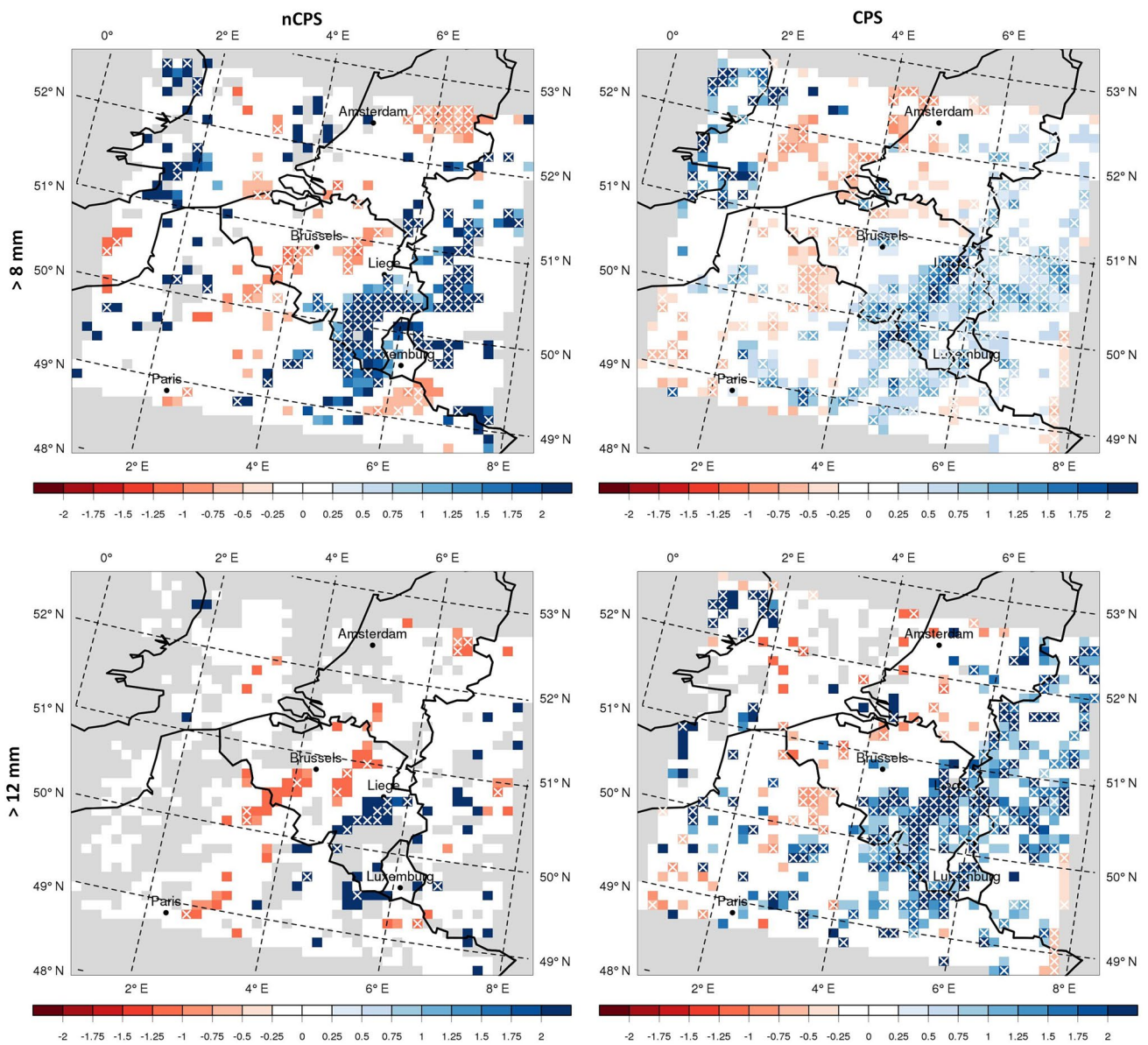
**Fig. 11** As Fig. 10, but for winter (DJF)

simulations not only simulate a larger number of daily extreme precipitation events during summertime, but during wintertime as well (Fig. 4). Yet, unlike for summer, the increase in the number of wintertime extreme events when moving from nCPS to CPS is large only for Flanders, and not for the Ardennes. A possible explanation for this difference could be that it is linked to a difference in geographical location, with Flanders located close to the North Sea whereas the Ardennes are located further inland. Therefore, the Ardennes are possibly more sheltered from wintertime convective storms, which can occur

in situations when a cold front coming in from the north passes over relatively warm North Sea waters. If this is indeed the case, then wintertime extreme convection in the Ardennes is caused more frequently by processes other than convection when compared to Flanders (e.g., large-scale stratiform precipitation and orographic uplift), possibly explaining why the difference in the number of extreme wintertime events between nCPS and CPS is smaller in this region.

Finally, note that the increase in wintertime extreme precipitation over Flanders when moving to CPS is not only





**Fig. 12** Maps of relative future change ( $[\text{future-present}]/\text{present}$ ) in number of events exceeding 8 mm/hour (top panels) and 12 mm/hour (bottom panels), for nCPS (left panels) and CPS (right panels), for summer daytime (12–20 UTC). CPS values were regridded to the nCPS grid. Only pixels for which the change is significant on the

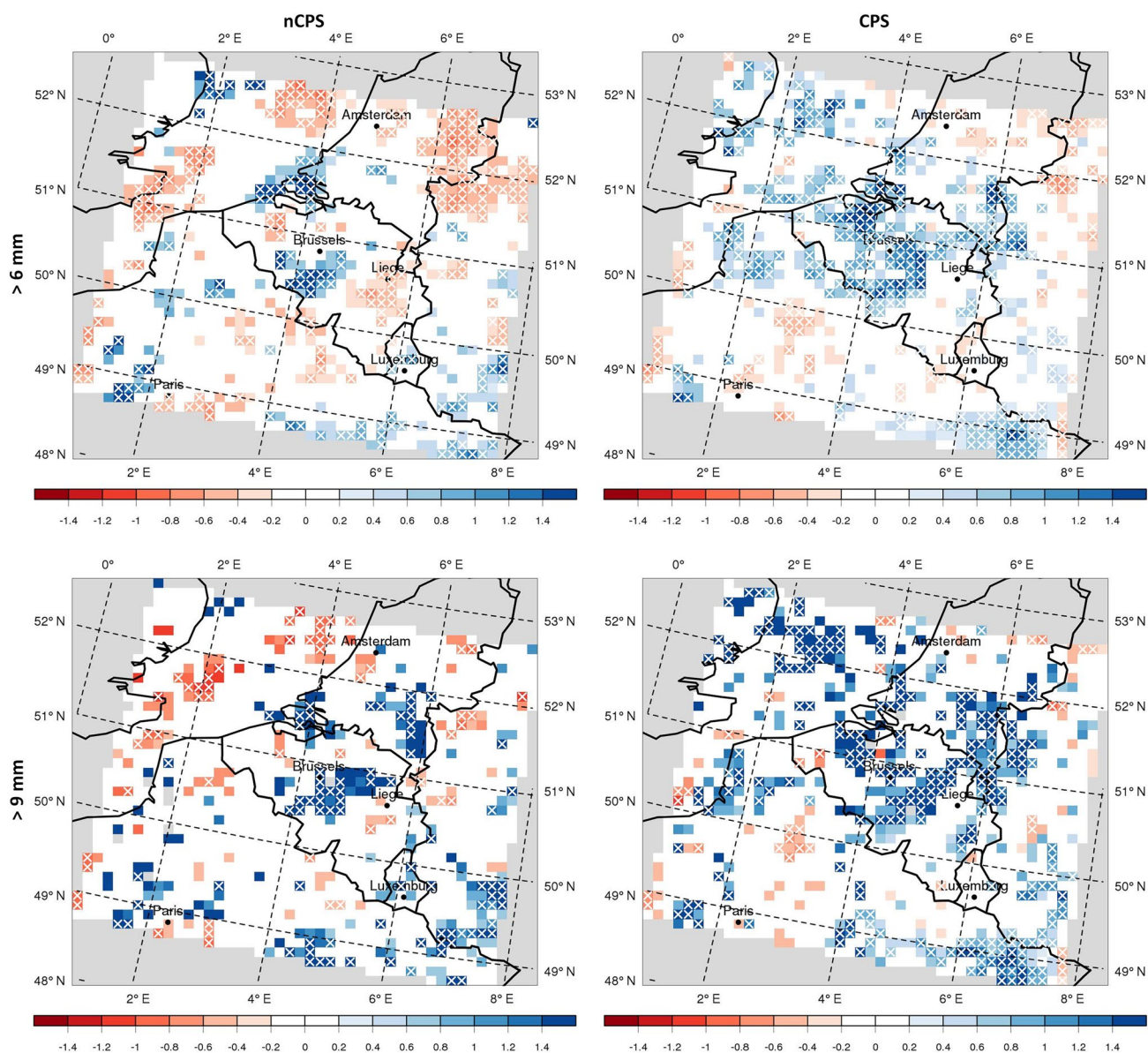
$p < 0.25$  level (Chi square test) are colored. A white asterisk is drawn for pixels for which the change is statistically significant on the 0.1 level. Pixels for which there are no events exceeding these thresholds for the present-day period are drawn in grey

present, but exceeds the increase during summertime, and leads to a larger overestimation when compared to the other seasons. This large overestimation could be linked to the specific characteristics of wintertime convective activity, which largely takes the form of relatively small single cell or air-mass thunderstorms (isolated thunderstorms with one main updraft). As previously discussed, this type of small scale cell is still under resolved at CPS, which leads to an overestimation of their intensity. Therefore, a further

increase in the horizontal resolution used for our CPS simulations could possibly help alleviate this positive wintertime bias.

#### 4.2 Extreme precipitation climate change signal

In summer, our CPS simulations project a higher increase of extreme daily accumulations when compared to our nCPS simulations, for both the flat and mountainous subdomains. Thus, the higher sensitivity of summer daily



**Fig. 13** As Fig. 12 but for summer nighttime, number of events exceeding 6 mm/hour (top panels) and 9 mm/hour (bottom panels)

extremes at CPS seems to be independent of domain topographic complexity. We can compare these results to a number of recent studies that have also looked at the extreme precipitation climate change signal of nCPS and CPS simulations on daily (and sub-daily) timescales (Table 2). For daily accumulations during summer, most studies report that extreme precipitation in CPS simulations is more sensitive to climate change (Chan et al. 2014a; Ban et al. 2015; Saeed et al. 2017), which is in line with our results. Also in line with our findings is that the higher sensitivity of summer daily extremes seems to be independent of domain topographic complexity, as these

studies include a variety of terrain types, ranging from mostly flat to mountainous.

For winter, our CPS simulations also predict a higher increase, but the difference with nCPS is smaller, and limited to the most extreme daily precipitation thresholds. Also, the difference is higher for our Ardennes sub-domain. As previously mentioned, winter precipitation over the Ardennes is mostly stratiform and orographic, so this difference is likely the result of a better resolved orography, rather than an improved representation of convective storms. It is also the only difference discussed that we can tentatively link to better resolved orography,

**Table 2** Overview of recent studies that compare extreme precipitation of simulations at nCPS and CPS, in terms of present-day performance (type eval.) and in terms of the future climate change signal (type cc.)

Study	Type	Timescale	Model	Location	Topography
Chan et al. (2013)	eval.	Daily/hourly	MetUM	Southern UK	Mostly flat
Ban et al. (2014)	eval.	Daily/hourly	COSMO-CLM	Alps	Mountainous
Chan et al. (2014a, b)	eval./cc	Daily/hourly	MetUM	Southern UK	Mostly flat
Kendon et al. (2014)	eval./cc	Hourly	MetUM	Southern UK	Mostly flat
Fosser et al. (2014)	eval.	Daily/hourly	COSMO-CLM	Southwest Germany	Mountainous
Ban et al. (2015)	eval./cc	Daily/hourly	COSMO-CLM	Alps	Mountainous
Brisson et al. (2016)	eval.	Daily/hourly	COSMO-CLM	Belgium	Mixed
Tabari et al. (2016)	eval./cc	Daily/3 hourly/hourly	ALARO and COSMO-CLM	Brussels	Flat
Fosser et al. (2017)	cc	Daily/hourly	COSMO-CLM	Southwest Germany	Mountainous
Saeed et al. (2017)	cc	Daily	COSMO-CLM	Belgium	Mixed

as all other CPS to nCPS differences are clearly linked to explicit convection. When comparing these results to existing literature, there are fewer studies to compare to, as most focus on the summer season. However, the studies that do report results for winter generally report that the difference between nCPS and CPS during winter is either smaller than during summer or non-existent (Chan et al. 2014a; Saeed et al. 2017), which is consistent with our results. Chan et al. (2014a), also looked at regional differences within their study domain (the southern United Kingdom) as we did here and found that the difference in extreme winter daily precipitation between CPS and nCPS was higher for the more mountainous sub-region Wales, which is in line with our findings for wintertime.

For the hourly timescale, our nCPS and CPS simulations both project a similar increase in summertime hourly extreme precipitation for the Ardennes region, during both daytime and nighttime. In contrast, for Flanders, our CPS simulations project a clear increase during daytime and nighttime, whereas our nCPS simulations project a decrease during daytime and a significantly smaller increase during nighttime. Our results thus show that, at least for our model and study domain, the difference in the summertime hourly extreme climate change signal between nCPS and CPS correlates with topographic complexity.

One possible reason why nCPS simulations are able to capture the increase in hourly extremes over areas with hilly, complex topography but not over lowlands is a difference in the mechanisms that trigger convection in these areas. For lowlands, convection can be triggered by the passage of large-scale weather systems (e.g. cold fronts), by differential heating of the land surface due to variability in surface characteristics (e.g. differences in land-use or land/sea contrasts); or by a combination of both. These mechanisms are also responsible for triggering convection over mountainous

regions but here, additional triggering mechanisms exist, namely orographic uplift and thermal flow induced by orography (e.g. anabatic and katabatic slope winds, valley winds, etc.).

Our results suggest that nCPS simulations are able to capture future increases in hourly summer extreme precipitation in regions where orographic features are an important triggering mechanism, but not in regions where other processes dominate. A recent study of future extreme precipitation for the Alps using a ~12 km nCPS ensemble seems to support this hypothesis, as this nCPS ensemble shows a future increase in summertime extremes for high Alpine elevations, against a background in which surrounding low lying areas are expected to become significantly drier (Giorgi et al. 2016). Also, the result was confirmed by a single CPS simulation, thus providing support for the hypothesis that nCPS and CPS simulations project similar future extreme precipitation increases in mountainous regions.

One possible mechanism which could explain this result is the fact that in mountainous regions, the scale of the boundary layer processes that precede and trigger deep atmospheric convection is influenced by topographical features, which leads to larger horizontal scales when compared to flat regions (Leutwyler et al. 2017). As previously mentioned, nCPS simulations have a tendency to overestimate precipitation when convective clouds approach or exceed grid scale. Possibly, for mountain regions, the future increase in large-scale convection triggered by orography could compensate for the general underestimation of the increase in hourly extremes associated with the other types of convective triggering. However, further research is needed to confirm this hypothesis, as an in depth study of differences in convection triggering mechanisms was outside of the scope of this study.

Note though, that some support for our hypothesis may be found in literature. Specifically, considerable disagreement exists between studies that compare the extreme climate change signal of nCPS and CPS simulations at this timescale, especially for the summer season. Of the few existing studies that discuss the hourly timescale, two report that the difference for summer is small or insignificant (Ban et al. 2015; Fosser et al. 2017), while three others report that the summer increase in extreme precipitation is significantly higher at CPS for all or a large part of the intensity spectrum (Kendon et al. 2014; Chan et al. 2014a; Tabari et al. 2016). The latter three studies used either the southern UK or the Brussels region as their study area, while the former two studies used either the Alps or southwestern Germany. As such, their reported results also appear to correlate with the complexity of the domain topography, as the southern UK and Brussels region are predominantly flat, whereas southwestern Germany and the Alps are both mountainous regions.

Finally, one important caveat worth mentioning in this discussion section is that, while nCPS simulations may match the relative increase in the number of events exceeding various extreme precipitation thresholds for the Ardennes region, they generally do not match the absolute increase. As shown in the “[Model evaluation](#)” section, nCPS simulations produce significantly less hourly extreme events for the present day. Therefore, an identical relative increase can be attained with a smaller absolute increase, e.g., both nCPS and CPS simulations project the number of events exceeding 9 mm/h during summer days to double, but for CPS the increase is from 17 to 33 events, while for nCPS the increase is from 4 to 8. This large difference in starting position should also be taken into account when interpreting results for wintertime. While winter daytime extreme events on the hourly timescale may increase more at nCPS than they do at CPS, this is unlikely to be the result of a difference in model dynamics, but is more likely linked to the difference in absolute number of present-day events.

## 5 Conclusion

This study addresses the possible added value of convection permitting scale (CPS) over non-convection permitting scale (nCPS) in simulating extreme precipitation, for both present-day climate as well as future climate projections. Compared to existing literature on these topics, important novelties for this study are the use of 30 year simulations (most existing studies use only 10-year simulations) and the choice of study area, which consists of both lowland and mountainous sub-regions, which are separated in the analysis.

Our present-day evaluation results mostly confirm existing literature on the topic. They show that in regions and during periods where convection contributes substantially to extreme precipitation, CPS simulations produce a significantly higher number of extreme events on both the daily and hourly timescale. For the hourly timescale, this increase is a clear improvement, as it increases correspondence with observations for both seasons. However, for daily extreme precipitation, the increase is not a clear-cut improvement over nCPS. The overestimation in the frequency of daily extreme precipitation events at CPS could possibly be linked to the fact that at the horizontal resolution currently employed in this study as well as most other CPS studies, (~ 1.5–3 km) convection is still under-resolved, leading to an overestimation of extreme precipitation from small convective cores. A further increase in horizontal resolution to sub-kilometer scale could help alleviate this problem, but is not yet feasible for climate simulations due to limitations in computational power.

Moving on to the future climate, both nCPS and CPS simulations project a future decrease in mean summer precipitation and an increase in mean winter precipitation over the study area. The magnitude of the respective increase and decrease is similar for both model setups, and can be linked to changes in large-scale circulation simulated by the driving GCM. Extreme precipitation, on the other hand, tends to increase in both seasons. On the daily timescale, both nCPS and CPS simulations project extreme precipitation to increase, but the increase is significantly higher for CPS. On the hourly timescale, CPS simulations project a summer increase for our lowlands and mountainous sub-region. nCPS simulations are only able to replicate this increase for the mountainous sub-region, but not for the lowlands.

The reason our analysis distinguished between these two sub-regions is a disagreement in existing literature addressing the difference in the future change of hourly precipitation extremes at CPS versus nCPS. Only a handful of studies have addressed this particular research question, with study areas including Brussels, the southern UK, southwest Germany and the Alps. Hourly extremes were found to increase significantly more at CPS for the southern UK and Brussels, but not for southwest Germany and the Alps. Our results suggest that this difference can be explained by the difference in topographic complexity, as the southern UK and Brussels are predominantly flat, whereas southwest Germany and the Alps are mountainous.

We hypothesize that the reason for the domain dependence present in our results as well as literature is a regional difference in the mechanisms that trigger convection. Triggering mechanisms over lowlands include the passage of large-scale weather fronts and differential surface heating. Over mountainous terrain, an additional triggering

mechanism exists, namely orography. Our results suggest that nCPS simulations are able to match CPS increases in hourly extremes in areas that include convection linked to or triggered by orography. A possible reason could be that nCPS overestimates the future increase in hourly extremes linked to orography, and therefore, matches the increase seen at CPS due to compensating errors. However, we did not directly investigate differences in triggering mechanisms in this study, so further research is needed to confirm this hypothesis.

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