Title

Consistent scale-dependency of future increases in hourly extreme precipitation in two convection-permitting climate models

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Key Words

CORDEX.be, convection-permitting simulations, COSMO-CLM, ALARO-0, extreme hourly precipitation, climate change, parameterization

Abstract

Convection-permitting models (CPMs) have been proven successful in simulating extreme precipitation statistics. However, when such models are used to study climate change, contrasting sensitivities with respect to resolution (CPM vs. models with parameterized convection) are found for different parts of the world. In this study, we explore to which extent this contrasting sensitivity is due to the specific characteristics of the model or due to the characteristics of the region. Therefore, we examine the results of 360 years of climate model data from two different climate models (COSMO-CLM driven by EC-EARTH and ALARO-0 driven by CNRM ARPEGE) both at convection-permitting scale (CPS, ~ 3 km resolution) and non-convection-permitting scale (non-CPS, 12.5 km resolution) over two distinct regions

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(flatland vs. hilly region) in Belgium. We found that both models show an overall consistent scale-dependency of the future increase in hourly extreme precipitation for day-time. More specifically, both models yield a larger discrepancy in the day-time climate change signal between CPS and non-CPS for extreme precipitation over flatland (Flanders) than for orographically induced extreme precipitation (Ardennes). This result is interesting, since both RCMs are very different (e.g. in terms of model physics and driving GCM) and use very different ways to represent deep convection processes. Despite those model differences, the scale-dependency of projected precipitation extremes is surprisingly similar in both models, suggesting that the this scale-dependency is more dependent on the characteristics of the region, than on the model used.

1 Introduction

One of the most severe consequences of climate change is the shift in intensity and frequency of extreme weather events (IPCC, 2013). Changes in extreme and intense precipitation are of particular concern, since they can have large impacts on society through the generation of floods, causing infrastructural damage and even human casualties.

Future projections of climate change impacts on extreme precipitation often rely on results obtained by General Circulation Models (GCMs), but the resolution of such models is too coarse to represent extreme precipitation events well (e.g. Tabari et al., 2016). Simultaneously, there exists a large demand for high-resolution climate information by stakeholders, creating a scale discrepancy between the information provided by GCMs and the information required for adaptation strategies. This scale gap can be overcome using the approach of downscaling based on Regional Climate Models (RCMs) (Wang et al., 2004; Maraun et al., 2010; De Troch, 2016; Saeed et al., 2017; Termonia et al., 2018).

RCMs have been demonstrated to add value with respect to their coarser resolution counterparts, especially in regions with complex topography (Wang et al., 2004). Owing to their higher resolution, the former models are able to account for more spatial details, such as a more realistic representation of orography and land-sea contrasts (Wang et al., 2004; Maraun et al., 2010; Prein et al., 2015; Saeed et al., 2017). Next to that, they additionally improve the treatment of fine scale physical and dynamical processes (Maraun et al., 2010; Kendon et al., 2012; Prein et al., 2016) and they also have been shown to add value in their representation of precipitation and precipitation extremes (Maraun et al., 2010; Tabari et al., 2016), especially on daily timescales (Kendon et al., 2012; Olsson et al., 2015; Maraun et al., 2010; Vanden Broucke et al., 2018). However, regional climate models at non-convection-permitting scales still show important deficiencies in their representation of precipitation extremes at sub-daily timescales (Maraun et al., 2010; Kendon et al., 2017a; Kendon et al., 2012; Vanden Broucke et al., 2018). The resolution of such climate models is still too coarse to explicitly resolve deep convection and therefore, they have to rely on error-prone convection parameterization schemes (Weisman et al., 1997). Common deficiencies are a misrepresentation of the diurnal cycle of convective precipitation (Kendon et al., 2012, 2014; Prein et al., 2015; Brisson et al., 2016; Maraun et al., 2010), an associated too early onset in convective activity (Fosser et al., 2014; Langhans et al., 2013) and a misrepresentation of hourly precipitation extremes (Prein et al., 2015).

Recent advances in high-performance computing power allowed refinement of RCM resolutions beyond the scale of 10 km (Prein et al., 2015). RCMs operating at such high resolutions (Convection-permitting Models (CPMs)) typically have resolutions of less than 4 km (Weisman et al., 1997), sufficient to allow for an explicit treatment of deep convection (Prein et al., 2015; De Troch, 2016), and thereby reducing uncertainties due to avoiding error-prone convection parameterization (e.g. Mooney et al., 2017). Recently, a number of studies demonstrated the added value of convection-permitting simulations compared to coarser resolution RCMs, mainly for sub-daily timescales (Prein et al., 2015, 2016; Vanden Broucke et al., 2018, De Troch, 2013, Kendon et al., 2019). The most prevalent improvements are a better representation of the diurnal cycle of convection (Kendon et al., 2012; Ban et al., 2014; Prein et al., 2013; Hohenegger et al., 2008; van Lipzig & Willems, 2015a; Fosser et al., 2014; Prein et al., 2015; Brisson et al., 2016; Langhans et al., 2013), an improved spatial precipitation distribution (Vanden Broucke et al., 2018; Ban et al., 2014; Warrach-Sagi et al., 2013; Prein et al., 2013; Hohenegger et al., 2008; Brisson et al., 2016) a better indication of high intensity summer precipitation events (Kendon et al., 2012; Ban et al., 2014; Prein et al., 2013; Chan et al., 2014b; Fosser et al., 2014; Brisson et al., 2016; Tabari et al., 2016; Vanden Broucke et al., 2018), and an improved representation of surface-atmosphere feedbacks (e.g. Hohenegger et al., 2009; Taylor et al., 2013). Next to that, also the formation of clouds related to different land use characteristics are better represented in CPMs (Vanden Broucke et al., 2017). Most studies also agree on the fact that, especially over mid-latitudes, the added value of CPMs is lower for the winter season than for the summer season (Chan et al., 2013; Fosser et al., 2014, Saeed et al., 2016, Vanden Broucke et al., 2018).

Many climate change studies have focussed on extreme precipitation, examining for example how extreme precipitation events may evolve under climate change and whether the projected changes differ between convection-permitting scale (CPS, resolution < 4km with explicitly resolved deep convection) and non-CPS (e.g. Vanden Broucke et al., 2018, Giorgi et al. 2016). Kendon et al. (2017), on the one hand, found that changes in seasonal mean precipitation and changes in precipitation occurrence show agreement between CPS and non-CPS for both the summer and winter season. On the other hand, different changes in intensity and duration as well as of daily extremes are found between CPS and non-CPS. The climate change signals are consistent among different studies in terms of larger increases in the intensity of daily precipitation extremes for CPS, especially during the summer months (Chan et al., 2014a; Ban et al., 2015; Saeed et al., 2017).

For hourly rainfall, however, projected changes in extreme precipitation vary widely among different studies and between different regions around the world. Some studies found larger increases for hourly precipitation extremes at CPS (Kendon et al., 2019, 2014; Tabari et al., 2016), while others reported little or no differences between CPS and non-CPS (Chan et al., 2014a; Ban et al., 2015; Fosser et al., 2017). According to Vanden Broucke et al. (2018), such differences could potentially be attributed to differences in topographic complexity of the regions under study. More specifically, for Belgium they found a higher sensitivity of extreme precipitation over flatlands compared to hilly areas. A similar dependency was found by Giorgi et al. (2016) over the Alps, with a different sensitivity of the precipitation extremes between the mountainous regions and the surrounding lower areas. Also in other regions around the world, differences in sensitivities with respect to topography are found (e.g. Prein et al., 2017, Shi et al., 2016, Stratton et al., 2018, Kendon et al., 2019), but sometimes with opposite signs or with no dependency on topography. An example of the former are Stratton et al. (2018) and Kendon et al. (2019) over Africa, and an example of the latter is Revadekar et al. (2011) over India, for which the topographical dependency of the extreme precipitation climate change signal is less clear cut. Moreover, regarding the magnitude of the increase in extreme precipitation not all studies agree.

Besides topography and scale, other factors can influence the climate change signal of precipitation extremes as well. Generally, results of (convection-permitting) climate simulations are largely model-dependent as a result of inherent uncertainties related to the modelling process (Coppola et al., 2018, Knutti et al., 2010). For example, differences in parameterization schemes between different climate models may contribute to parametric uncertainties but also differences in model physics or differences related to the driving climate model can result in different outcomes regarding the climate change signal (Knutti et al., 2010). Next to that, internal climate variability is a major additional source of uncertainties (e.g. Deser et al., 2012). CPMs are often not able to sample this uncertainty since they are too computationally expensive to be integrated for extended periods (i.e. hundreds of years). Therefore, it is important to consider such factors that may contribute to many uncertainties in the climate change signal of the extremes.

The aim of this paper is to explore whether sub-daily extreme precipitation signals differ between different regional climate models. More specifically, we want to examine to which extent the contrasting sensitivities between CPS and non-CPS that are found in previous studies can be attributed to either the specific characteristics of the model (e.g. different ways to simulate deep convection) or to the characteristics of the region (topography). We do this by comparing the output of two different regional climate simulations over a region with a heterogeneous landscape (Belgium), both at CPS (allowing for explicit resolved convection) and non-CPS (deep convection fully parameterized). The corresponding research question that we want to answer in this study is: "Do sub-daily extreme precipitation signals differ between different regional climate models?" With "extreme precipitation signals" we thereby refer to 1) the dependency of the climate change signal to topography (flatland vs. low mountainrange) and scale (CPS vs. non-CPS) 2) the dependency of the climate change signal to the daily cycle (day vs. night), 3) the dependency of the climate change signal to the extreme precipitation intensity and 4) the difference between extreme and seasonal mean precipitation. For this purpose, we make use of twelve sets of 30-year (in total 360 years of) climate simulations over Belgium from the COordinated Regional climate Downscaling EXperiment (CORDEX.be, more information via Termonia et al. (2018) or via http://www.euro-cordex.be/). Extreme hourly precipitation statistics are examined based on two different regional climate models (COSMO and ALARO-0) for two separate regions in Belgium with different surface characteristics (flatland vs. hilly regions) and at two different spatial scales (CPS and non-CPS).

The paper is organized as follows: Section 2 provides the information about the climate simulation data and regional climate models that were used in this study, as well as the methodology that was used. The results are described in section 3 and a discussion about all the key-results is provided in section 4. In the last section (5), a general conclusion is formulated.

2 Data and methods

2.1. Model simulations

Different sets of high-resolution climate model simulations based on two different RCMs (COSMO-CLM and ALARO-0) were used. These model runs were set up by different Belgian research institutions[2] and were coordinated and provided by the CORDEX.be community. All the CORDEX.be climate simulations were performed using a one-way nesting approach by which both a coarse resolution run (12.5 km) and a high resolution run at convection-permitting

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Royal Meteorological Institute of Belgium (RMI) scale (CPS, 2-4 km) were provided for each model. In the remainder of this study we will use the term 'CPS' to refer to simulations at convection permitting scale (2.8 or 4 km), while with 'CPM' we refer to a convection-permitting regional climate model (ALARO-0 or COSMO-CLM) that is run at CPS with deep convection explicitly resolved, either fully (COSMO-CLM) or partially (ALARO-0).

The coarse resolution runs were performed over the EURO-CORDEX domain (Giorgi et al., 2009) at a resolution of 0.11 degrees and the CPS runs were performed over the domain of Belgium with a resolution of 0.035 and 0.025 degrees for the ALARO-0 and COSMO-CLM model, respectively (see fig. 1 and De Troch et al., 2013). Using the one-way nesting strategy, lateral boundary conditions for each of the climate model runs were provided by the coarser resolution model run. For the CPS runs, lateral boundary conditions from the RCM runs were imposed, while for the RCM runs boundary conditions were driven either by a GCM or ERA-Interim re-analysis data (Dee et al., 2011). For each model, three different types of model runs were performed: an evaluation run, a control run and a future run (fig. 2).

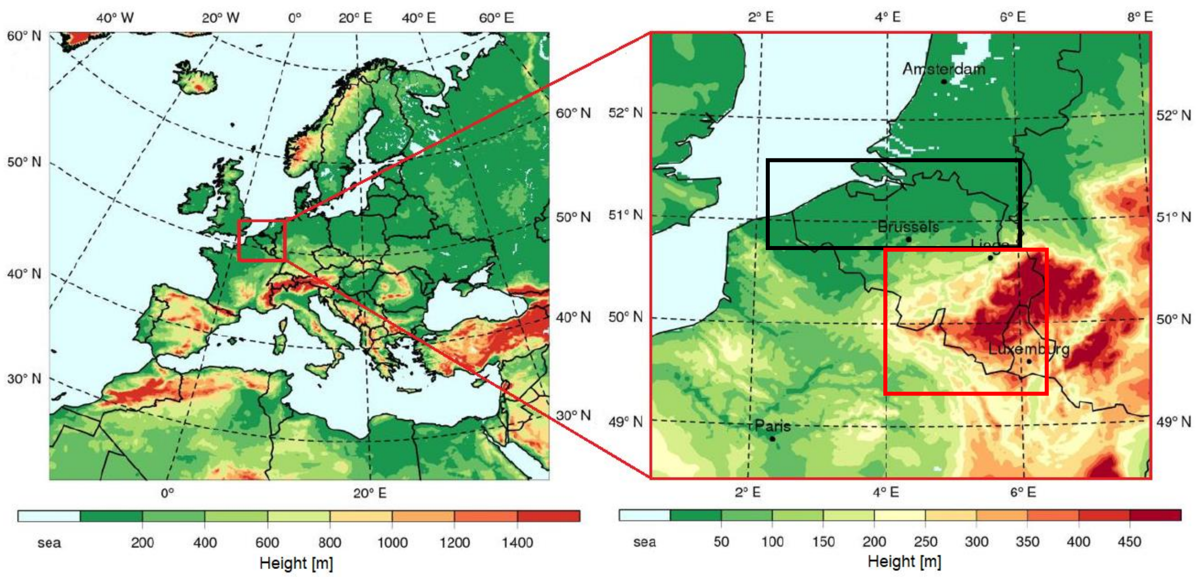

Fig. 1: Domain size and topography for the CORDEX.be non-CPS runs (12.5 km resolution) over Europe (left) and CPS runs (2.8 or 4 km resolution) over Belgium (right). Figure adapted from Vanden Broucke et al. (2018). Flanders is indicated by the black rectangle, the Ardennes by the red rectangle.

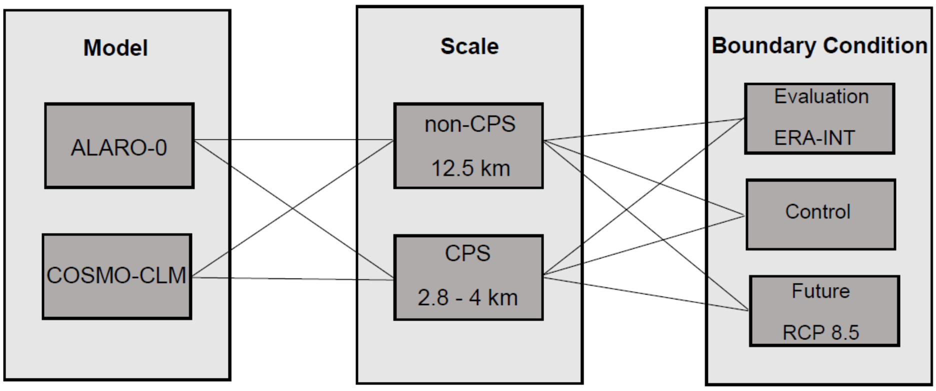

Fig. *2*: A schematic overview of the climate model simulations from CORDEX.be, used in this paper. Convection-permitting scale is abbreviated with CPS, while non-CPS refers to non-convection-permitting scale. Note that both models differ in scale and the way to represent deep convection.

The evaluation simulations were performed for the historical period of 1979-2010 for both climate simulations with the COSMO-CLM model and for the period of 1950-2010 and 2000-2011 for the CPS and non-CPS evaluation simulation with ALARO-0 respectively (table 1). The control simulations were performed for the historical period of 1975-2005 both at non-CPS scale and at CPS. Boundary conditions for the CPS runs were provided by different GCMs from the CMIP5 project (Taylor et al., 2012). In this paper we used the RCP 8.5 scenario (Van Vuuren et al. 2011; Riahi et al., 2011) in order to make climate projections for the end of this century (2070-2100).

Table *1*: Overview of the used climate model simulations.

Regional Climate Model	Institution	Simulation ID	Resolution (km)	Time Period	Driving global dataset
COSMO CLM	KUL	EU hindcast	12.5	1979-2010	ERA-INTERIM
		BE hindcast	2.8	1979-2010	ERA-INTERIM
		EU control	12.5	1975-2005	ECEARTH
		BE control	2.8	1975-2005	ECEARTH
		EU future	12.5	2070-2100	ECEARTH RCP 8.5
		BE future	2.8	2070-2100	ECEARTH RCP 8.5
ALARO-0	RMI	EU hindcast	12.5	2000-2011	ERA-INTERIM
		BE hindcast	4	1950-2010	ERA-40/ ERA-INTERIM
		EU control	12.5	1975-2005	CNRM-CM5 ARPEGE
		BE control	4	1975-2005	CNRM-CM5 ARPEGE
		EU future	12.5	2070-2100	CNRM-CM5 RCP 8.5
		BE future	4	2070-2100	CNRM-CM5 RCP 8.5

2.2. Model description and setup

2.2.1. COSMO-CLM[3]

The regional climate model COSMO (COnsortium for Small Scale MOdelling) is a non-hydrostatic model that can be used both for Numerical Weather Prediction (NWP) and in CLimate Mode (CLM) for the purpose of regional climate modelling. This model was originally developed by the German Weather Service (DWD) to be used for NWP purposes and is later adapted to be used for long term climate simulations. The COSMO model is now used and further developed for climate related applications by the CLM-Community, an international network of scientists from different research institutes from all over Europe (Rockel et al., 2008). The model has a non-hydrostatic core for atmospheric dynamics and contains parameterizations for radiative transfer, cloud microphysics, subgrid-scale turbulence and convection, ground heat and water transport and land-atmosphere interactions (Wouters et al., 2016).

The COSMO-CLM simulations were performed with version 5.0 of the COSMO CLM model. All simulations were executed using the Runge-Kutta two-level time stepping scheme and the Ritter-Geleyn radiation scheme (Ritter & Geleyn, 1992). Moist convection was parameterized using the Tiedtke scheme (Tiedtke, 1989) in the non-CPS simulations, while at CPS deep convection was resolved explicitly and the deep convection scheme was switched off with only shallow convection parameterized. For cloud micro-physics, the schemes of Doms (2007) and Baldauf-Schultz were used (Doms et al., 2011; Baldauf & Schultz, 2004). The urban land-surface model TERRA_URB (Wouters et al. 2012, 2015, 2016, 2017; Demuzere et al., 2017) was implemented, instead of the TERRA_ML scheme. All simulations were performed with 40 vertical layers (between 0 and 25 km height) and with timesteps of 20 and 80 seconds at CPS and non-CPS respectively.

Lateral boundary conditions for the COSMO-CLM RCM climate simulations (with an update frequency of 6 hours) were provided by the GCM EC-EARTH (table 1), which is part of the CMIP5 multi-model ensemble used in the AR5 of the IPCC (Cubasch et al., 2013). One of the 16 members of the EC-EARTH ensemble was downscaled to provide the lateral boundary conditions for the COSMO-CLM RCM runs. For this purpose, the median member of the ensemble was chosen, which is the first member of the EC-EARTH ensemble (for more information see section 2.1 in Vanden Broucke et al., 2018). For our model setup in the COSMO-CLM simulations, the recommendations from Brisson et al. (2015) were taken into account.

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[3] More information about COSMO-CLM can be found at www.clm-community.eu

2.2.2. ALARO-0

The ALARO-0 model is a hydrostatic model developed within the ALADIN (Aire Limitée Adaptation Dynamique Développement International) community. It is a model version of the ALADIN model, which is the Limited Area Model (LAM) version of the French global ARPEGE-IFS model (Action de Recherche Petite Echelle Grande Echelle Integrated Forecast System) (Bubnová et al., 1995). The ALARO-0 model was originally developed for the purpose of NWP and runs operationally in the countries of the ALADIN consortium. More recently, this model is also used in the context of regional climate modelling (Termonia et al., 2018; De Troch, 2013). The ALARO-0 model was further developed by the Royal Meterorological Institute of Belgium (RMI).

The ALARO-0 simulations were based on the dynamical core of the ALADIN model (Bubnová et al., 1995) but employed different physics routines for radiation, microphysics and convection, cloudiness and turbulence (Giot et al., 2016; De Troch et al., 2013). The ALADIN dynamical core is based on a semi-implicit semi-Lagrangian timestepping scheme permitting timesteps of 300 seconds. For radiation the ARPEGE scheme was used (Ritter & Geleyn, 1992) while for convection and microphysics the Modular Multiscale Microphysics and Transport (3MT) package was used in combination with a prognostic-type microphysics scheme (Geleyn et al., 2008). The 3MT package was originally developed by Gerard & Geleyn (2005) and further developed and adapted by Gerard (2007) and Gerard et al. (2009). These new physical parameterization schemes have been specifically designed to be used at resolutions in the so-called “grey zone” of convection (below 10 km and above 500 m) at which convection is partially parameterized and partially resolved. In contrast to COSMO-CLM which switches off convection at CPS, ALARO-0 uses both at CPS and non-CPS the same scale-dependent parameterisation scheme. ALARO-0 furthermore employed a semi-Lagrangian horizontal diffusion scheme (Vana, 2008), a pseudo-prognostic turbulent kinetic energy scheme and the land surface model of Noilhan & Planton (1989). All simulations were performed with 46 vertical levels (from the surface to the 4 Pa level) and with time steps of 300 seconds for the non-CPS simulations and 180 seconds for the simulations at CPS. Lateral boundary conditions for ALARO-0 were provided by the GCM NCRM-CM5 ARPEGE (table 1), which is also part of the CMIP5 multi-model ensemble used in the AR5 of the IPCC (Cubasch et al., 2013).

Both COSMO-CLM and ALARO-0 have a resolution-dependent topography. As a result of that, the CPS simulations yield a higher degree of topographic detail compared to the coarser non-CPS simulations.

2.3. Climatology of the study regions

We focus our analysis on two separate regions of Belgium: Flanders (northern part, black rectangle in Fig. 1) and the Ardennes (southern part, red rectangle in Fig. 1). Both regions have different characteristics with respect to topography, the degree of urbanisation, population density and climatology. Flanders is a relatively flat region, with generally heights between 0 and 200 metres, while the Ardennes are characterised by a more hilly landscape (low-mountain range) with a maximal height of about 694 metres (Fig. 1). Flanders is densely urbanised and characterized by high population densities, whereas the Ardennes is a sparsely populated, more natural area with large patches of forest on the slopes of the low-mountain ranges. Both regions also differ in their climatology. Mean annual temperatures are about 3 degrees lower over the Ardennes compared to Flanders. Due to the orography effect (uplift) in the Ardennes, this region receives annually also more precipitation compared to Flanders. Mean annual precipitation over the Ardennes varies between 800 mm in the north and up to 1500 mm over the areas with highest elevation. Annual precipitation in Flanders varies between 750 mm near the coast and 850 mm further inland.

2.4. Methods

A model evaluation of both models (see Supplements) clearly indicates the added value of CPS versus non-CPS, consistent with the existing literature (see introduction).The main focus of this study is on the future climate projections of extreme precipitation. We focus our analysis on two topographically-different regions in Belgium. The northern “Flanders” region comprises Flanders, a small part of the southern Netherlands, parts of the North Sea and a very small part of northern France. The southern “Ardennes” region comprises of a large part of Wallonia, western Luxembourg and a small part of northern France (see fig. 1). Since the added value of CPMs for investigating precipitation changes is largest for summer months (see introduction), we focus our analysis on the summer months (JJA). Next to that, the summer season is also the season with highest convective activity in Belgium, providing an extra motivation to focus our analysis on this season (e.g. Goudenhoofdt et al., 2013). We also make a distinction between day- (12-18 UTC) and night-time (00-06 UTC), in order to test the sensitivity of the extreme precipitation statistics to the time period. During the day, convective activity is largest, while the opposite is true for the nigh-time period, when you have usually less convection and a dominance of large-scale synoptic systems.

For our statistical methodology to analyse rainfall extremes, we used a frequency-based method based on percentile thresholds (see e.g. Vanden Broucke et al. (2018)), focussing on both wet and dry days (as suggested by Schar et al. (2016)). More specifically, for a set of extreme percentile thresholds ranging from the 95th until the 99.995th percentile, the corresponding precipitation intensities (mm/hr) were derived for each model simulation and for the observations. For the model evaluation, the frequency of exceedance was determined for each grid-cell out of the subdomain (Flanders & Ardennes), both at CPS and non-CPS and compared the observational precipitation intensities. In order to avoid double-counting of extreme events, a block bootstrapping was applied to the data before calculating the exceedance frequencies. To determine the relative climate change signal, the exceedance frequencies from the control and future simulation were divided and plotted. For these simulations, we calculated the percentile exceedance using the precipitation intensities of the subsequent CPS model simulations of each model. To make a consistent comparison possible between CPS and non-CPS, the CPS data was regridded to the non-CPS grid. The latter does not influence the results much, as comparison between CPS and regridded-CPS were found to be small (Vanden Broucke et al. 2018).

As extreme precipitation signals can be highly uncertain due to the often small sample sizes, we performed a bootstrapping on our datasets to provide some uncertainty measures on the extreme precipitation climate change signals. Via a bootstrapping algorithm, we calculated from the original precipitation time series 1000 random resampled time series from which 10 percent of the original data was omitted, and calculated the exceedance frequencies and related relative future changes. From this, we obtained a distribution of 1000 possible extreme precipitation exceedance frequencies and their relative future changes, from which we calculated the mean, and the mean signal +/- two standard deviations. This range of two standard deviations around the mean is then plotted on the figures, as a measure of uncertainty for the future change signal. Using a student t-test, the statistical significance of the climate change signal was determined at a significance level of 0.01, in order to determine whether the projected signal differed from the control signal.

3 Results

3.1. The effect of topography (flat vs. low mountain) and scale (CPS vs. non-CPS)

There is a clear difference between the projected changes of the CPS and non-CPS simulations for the orographically-flat Flanders region during the day (Figs. 3 a & b). At CPS, both models on average project an increase in hourly precipitation extremes during day-time, up to 65% (20-100%) for COSMO-CLM and 80% (35-120%) for ALARO-0. For all CPS simulations, the relative changes in the threshold exceedance increase more for higher precipitation thresholds. The increase in hourly precipitation extremes as seen for the CPS runs is, however, in stark contrast to the non-CPS runs that on average project either small relative changes (ALARO-0) or negative changes (COSMO-CLM) for the day-time period (Figs. 3 a & b). Taking into account the uncertainty ranges around the mean signal, it is apparent that the differences between CPS and non-CPC projections are more outspoken for COSMO-CLM than for ALARO-0.

In contrast to the Flanders region, the day-time differences between CPS and non-CPS are much smaller in both models for the hilly area of the Ardennes (Figs 3 c & d). Both CPS and non-CPS project increasing relative changes of day-time extreme hourly precipitation. The increase in the frequency of the hourly extreme precipitation events for the day-time period is also larger for the Ardennes region (60-300% increase) than for Flanders (maximally 120% increase). In the Ardennes, both COSMO-CLM and ALARO-0 simulate an increase in the number of extreme precipitation events over nearly the whole percentile range, while in Flanders the increase is consistent across models for only the upper percentiles.

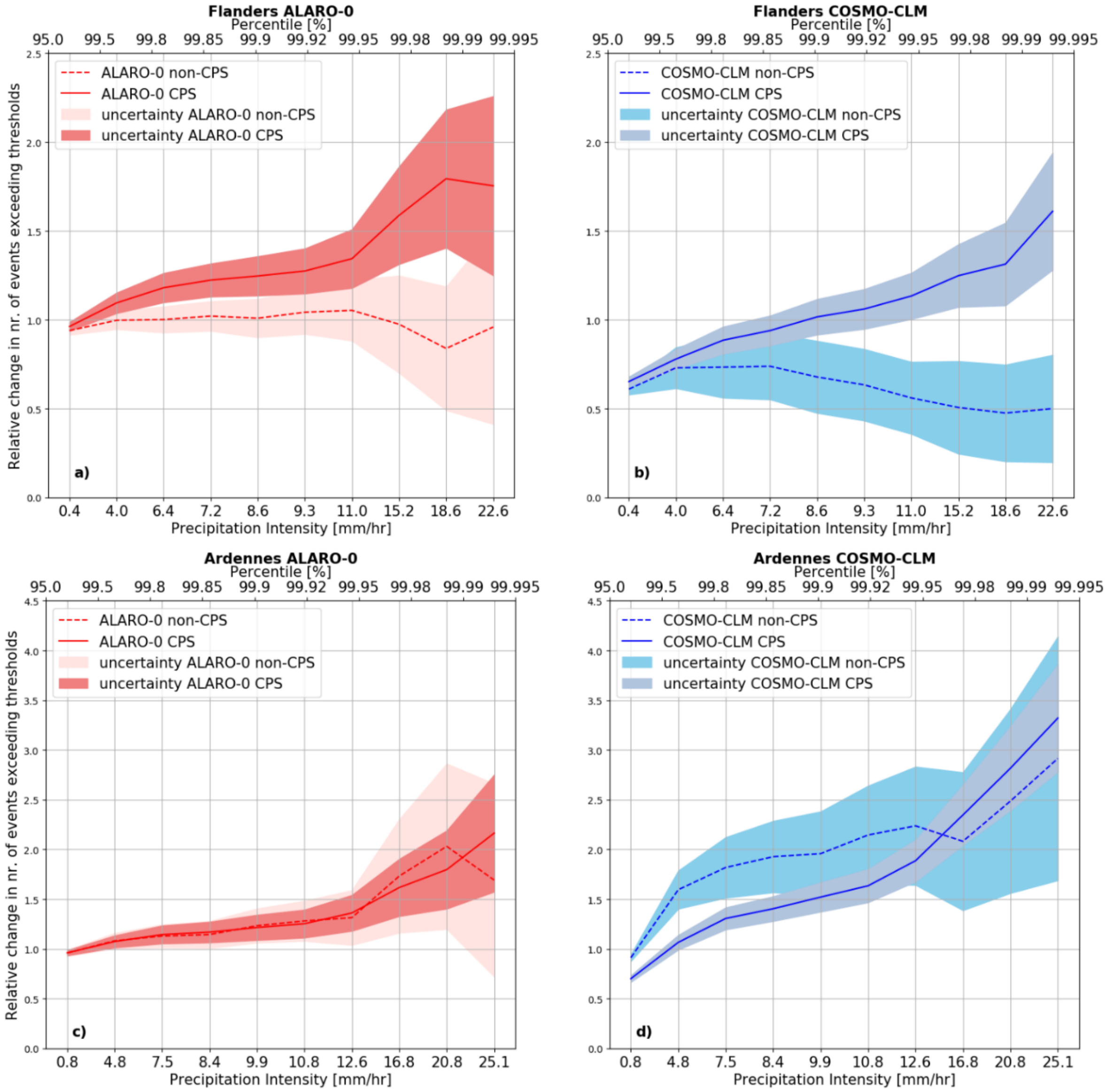

Figure 3: The end-of-the-century (2070-2100) relative change (future/present) in the exceedance frequency of different extreme hourly precipitation intensities during summer (JJA) for Flanders (upper panels, a & b) and the Ardennes (lower panels, c & d) for the day-time period (12-18 UTC). Values higher than one indicate an increase in extremes, while one means no change. Note that the precipitation intensities at the bottom of each figure are the mean of the intensities of all CPMs corresponding to the percentiles indicated at the top of the figure. Note that the scale of the y-axis differs between the upper and lower panels. Note also that all changes were found to be statistically significant, except for P95 of ALARO-0.

3.2. Dependency to the daily cycle (day vs. night)

There are considerable differences between the extreme hourly precipitation climate change signals for the day-time (Fig. 3) and night-time (Fig. 4). Both CPS and non-CPS models project an increase of the night-time extremes for both Flanders and the Ardennes region. In contrast to the day-time, the COSMO-CLM CPS vs. non-CPS differences are negligible, whereas ALARO-0 shows different changes between CPS and non-CPS, consistent with the day-time

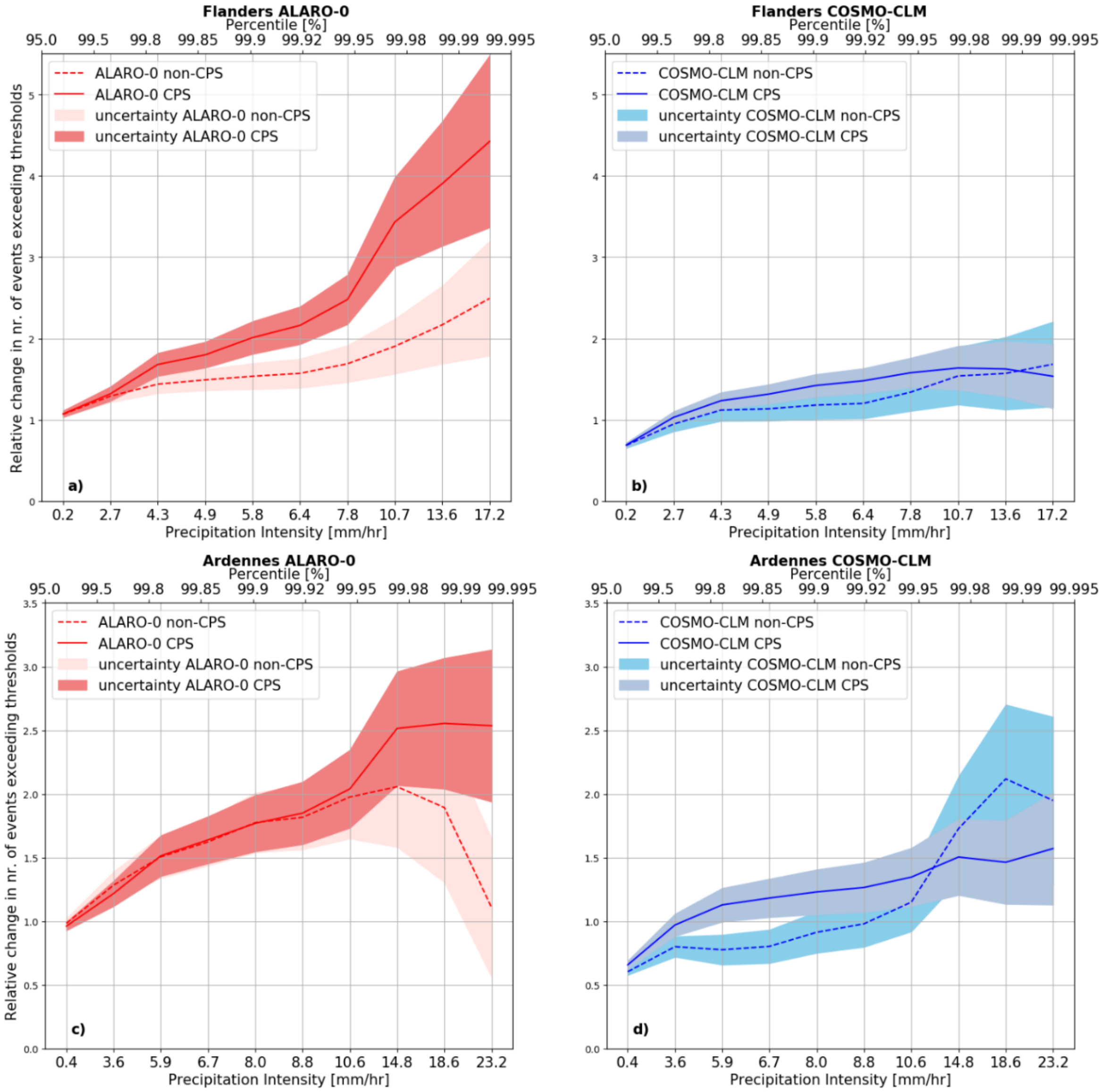

Figure 4: The end-of-the-century (2070-2100) relative change (future/present) in the exceedance frequency of different extreme hourly precipitation intensities during summer (JJA) for Flanders (upper panels, a & b) and the Ardennes (lower panels, c & d) for the night-time period (00-06 UTC). Values higher than one indicate an increase in extremes, while one means no change. Note that the precipitation intensities at the bottom of each figure are the mean of the intensities of all CPMs corresponding to the percentiles indicated at the top of the figure. Note also that the scale of the y-axis differs between the upper and lower panels.

signals. For the night-time period, the ALARO-0 CPS simulation also shows a much higher climate change signal for Flanders (on average up to 350%) compared to the non-CPS (up to 150%) and COSMO-CLM simulations (50-150%). For the Ardennes, the night-time projected changes in hourly extreme precipitation are very similar at CPS and non-CPS both for COSMO-CLM and ALARO-0, except for the ALARO-0 highest percentiles.

3.3. Intensity dependency

The climate change signals also show a clear dependency on the intensities of the extreme precipitation event (or the extreme precipitation percentile) (Figs. 3 and 4). Especially at CPS, the highest increase in the number of extreme precipitation event is expected for the higher-intensity events (upper percentiles). However, since such high-intensity events are extreme and rare, the uncertainty of the climate change signal is also largest for those events with the highest precipitation intensity. The differences between CPS and non-CPS also show a dependency on the intensity, as the difference between both is larger for the higher percentiles compared to the lower percentiles (especially for Flanders during day-time).

3.4. Extreme hourly precipitation vs. seasonal average precipitation

Beside the consistent climate change projections for extreme hourly precipitation between COSMO-CLM and ALARO-0, both models show a differential climate change signal for mean summer precipitation (Fig. 5). COSMO-CLM (driven by EC-EARTH) shows an overall drying, while ALARO-0 (driven by CNRM ARPEGE) simulates a slight increase in mean summer precipitation over large parts of the domain, especially over the northern part. Both models show the drying over the southern and south-eastern part of the country. COSMO-CLM and ALARO-0 also project a decrease in the rainy-hour frequency (number of events > 0.01 mm/hr), by the end of this century both at CPS and non-CPS (not shown). Although both models project a decrease in the rainy-hour frequency, the magnitude of this decrease considerably varies between COSMO and ALARO-0 with a higher decrease projected by COCMO-CLM, which is in line with the projections of the mean summer precipitation.

4. Discussion

4.1. The effect of topography (flat vs. low mountain) and scale (CPS vs. non-CPS)

Both COSMO-CLM and ALARO-0 project an increase in the number of extreme hourly precipitation events during day-time at CPS for Flanders, while this increase is not seen at non-CPS, especially for COSMO-CLM. For the Ardennes, the increase in the future events is found both at CPS and non-CPS, consistently for both models. Our results point thus towards a dependency of the climate change signal of the hourly extreme precipitation events on both the resolution (CPS vs. non-CPS) and the regional topographical characteristics (flatland vs. low-mountain range), that is consistent between the two regional climate models. A comparison between the precipitation statistics for Flanders and the Ardennes showed a small positive correlation between both regions. However, as we showed in our analysis, we see a clear difference in the extreme precipitation statistics between both regions, suggesting that their distinct land characteristics (especially orography) are important control parameters modulating the precipitation intensity, frequency and its climate change signal.

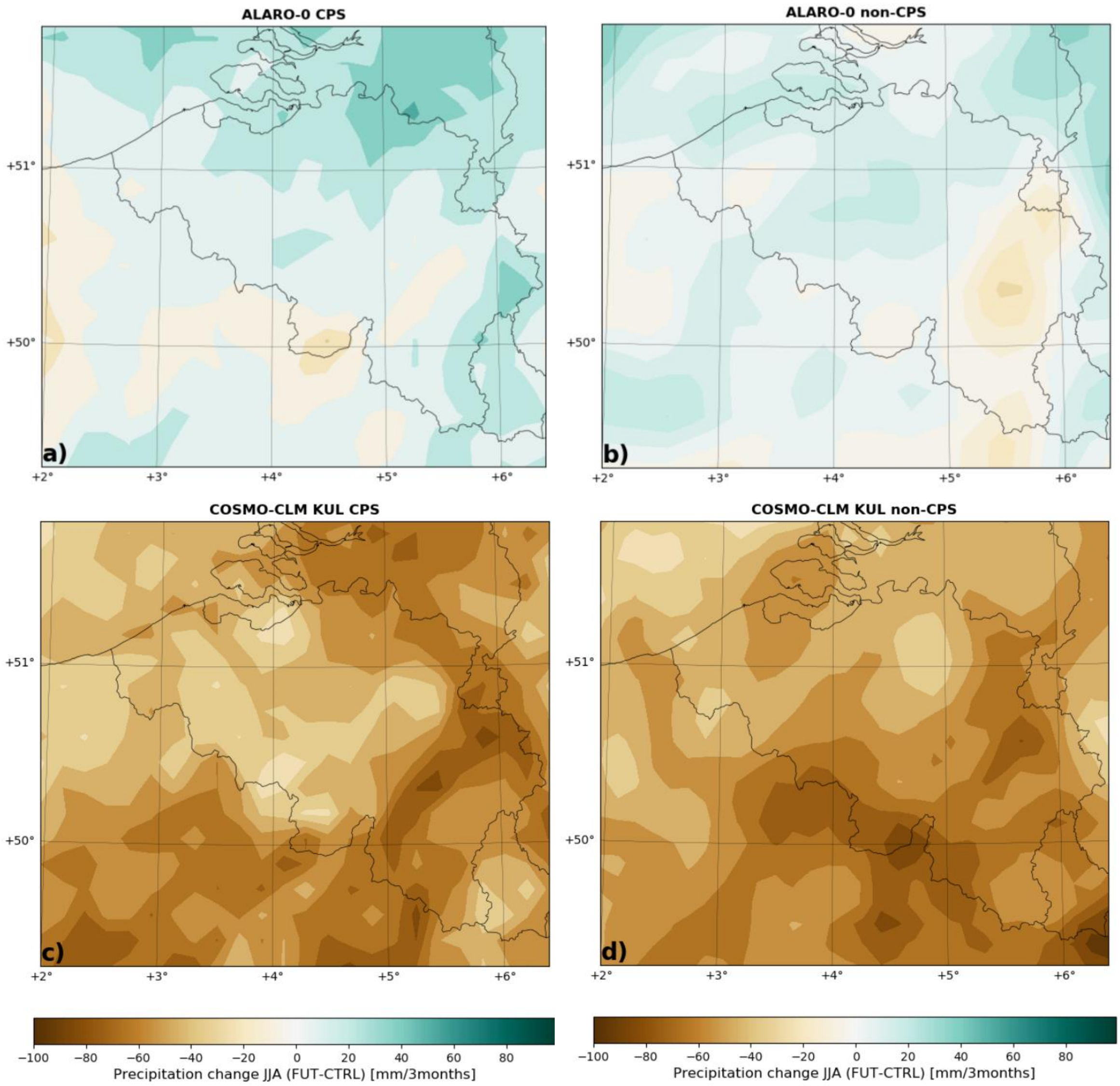

Figure *5*: **The end-of-the-century (2070-2100) projected change (future-present) in mean summer precipitation (JJA) for Belgium for ALARO-0 (top panels, a & b) and COSMO-CLM ALARO-0 (lower panel, c & d), at CPS (left panels, a & c) and non-CPS (right panels, b & d). The percentiles are calculated on all events over the domain.**

Recently, Vanden Broucke et al. (2018) found a similar topography- and scale dependency of the extreme hourly precipitation over our study domain (Belgium), using only the COSMO-CLM data. Here we found thus that this dependency seems to be independent on the regional climate model that is used, at least for our domain under study. Similar to our findings, Vanden

Broucke et al. (2018) also found for COSMO-CLM a higher resolution dependency of the hourly precipitation climate change signal for flatlands (Flanders) compared to hilly areas (Ardennes) and related this topography-scale dependence to the difference in the trigger mechanisms of convection between both types of regions. Extreme precipitation over flatlands such as Flanders is predominantly generated by convection through differential heating over land, a process that is generally not well represented by model simulations using parameterized convection. On the contrary, extreme precipitation over hilly areas is triggered by forced convection over the orography (with orographic uplift), which is taking place at larger scales that can be resolved at coarser scales already, even in models employing parameterized convection. Our study confirms thus the hypothesis of Vanden Broucke et al. that non-CPS simulations are able to capture the day-time increase in hourly precipitation in regions where orography is an important trigger, but not in areas where other processes dominate the triggering of convection and extreme precipitation. However, as discussed in the introduction, studies for other regions around the world point towards diverging conclusions regarding the scale-topography dependency. Since we here only considered two different CPMs and one study region, more similar studies employing other CPMs over other topographically-diverse regions will be needed to generalize our findings.

As we found a consistent topography-scale dependency in the day-time hourly extreme precipitation climate change signal for both COSMO-CLM and ALARO-0, our results suggest that the climate change signal for the extremes over our study domain is not sensitive to the way convection is treated in both models. As mentioned in the model description (section 2.2), the ALARO-0 model employs a specific scale-dependent deep convection parameterization scheme (De Troch, 2016; Gerard et al., 2005, 2007, 2009), while deep convection parameterization in COSMO-CLM is scale-independent. More specifically, deep convection parameterization in ALARO-0 is only activated for the scales that cannot be resolved by the grid. In the case of COSMO-CLM, the deep convective parameterization is fully switched on at non-CPS (and fully switched off at CPS). Those differences in parameterization mechanisms result in differences in the performance of both models between CPS and non-CPS for the present-day climate (Supplementary material figs. S2 and S3), with similar results at CPS and non-CPS for ALARO-0 and scale-divergence for COSMO-CLM. The latter is supported by Gao et al. (2017), who also found a reduced sensitivity to the model resolution for a scale-aware regional climate model similar as ALARO-0. As such, the different treatment of deep convection in both models seems to affect the performance of extremes in the present-day climate but does not seem to affect the CPS/non-CPS dependency of the future climate change signal, for which both models show a consistent sensitivity to the model resolution.

4.2. Daily cycle dependency (day vs. night)

For the night-time, when convective activity is generally lower, all simulations project an increase in the number of extreme hourly precipitation events, both for Flanders and the Ardennes. For COSMO-CLM the difference between CPS and non-CPS is much lower than for ALARO-0, especially for Flanders. This seems to suggest that the clear topography-scale dependency, as found for the day-time period, is not valid for the night-time extreme events, that are generally much less frequent and can have other origins than day-time extreme precipitation events. Moreover, ALARO-0 also showed much higher night-time changes for Flanders. We think that this might be related to the higher climate change signal that this model also shows for mean summer precipitation, but more research is needed in order to explore the origin of these high night-time differences more in detail.

4.3. Intensity dependency

Our study points out that the climate change signal of extreme hourly precipitation events is dependent on the precipitation intensity, or the percentile that is considered. We generally find higher future increases in the frequency of the events for the highest-intensity events (upper percentiles). This is in line with Pendergrass (2017), who states that the most extreme events have a different (stronger) response with respect to the climate warming, than the less extreme events. However, they also state that the changes in extreme precipitation statistics depend on the metric that is used. Here we used a frequency-based method based on thresholds and found that the frequency of the highest-intensity events are expected to increse more by the end of this century compared to the less-extreme events (at least for our study domain), this in addition to the increase in intensity that Pendergrass (2017) discusses.

4.4. Extreme hourly precipitation vs. seasonal average precipitation

The magnitude of the climate change signal showed a considerable difference between both models, for extreme hourly precipitation, as well as for mean summer precipitation. The effect of the different driving GCMs behind both RCMs is clearly visible in the climate change signal of mean summer precipitation (Fig. 5). Due to differences between the driving GCMs (ARPEGE vs. EC-EARTH), both RCMs reproduce a different (opposite) change pattern of mean summer precipitation over the study domain. The mean summer precipitation climate change signal is strongly determined by the synoptic forcing prescribed by the Global Circulation Models (GCMs), while the hourly extreme precipitation statistics are influenced by the other factors as well. For example, COSMO-CLM is a non-hydrostatic model, while ALARO-0 is hydrostatic. Next to that, ALARO-0 and COSMO-CLM also differ in their physics and land cover parameters. Moreover, as discussed in section 4.1., also the treatment of deep convection differs between both models. Disentangling the influence of all those different factors on the results is, however, out of the scope of this study.

Our results seem to indicate that CPMs produce more robust climate change signals for extreme precipitation (see previous paragraphs) compared to their projected signals for seasonal average precipitation, which are largely driven by the synoptic forcing, induced by their driving GCMs. Although, this is not a particular failing of CPMs, since the non-CPS models show similar large differences at these seasonal scales. This opens opportunities for combining micro-ensembles of just a few CPM members with larger standard RCM ensembles to create scenarios for both seasonal average and extreme precipitation.

5. Conclusions and outlook

Within this paper, summer hourly extreme precipitation events were studied over Belgium using two convection-permitting models (CPMs) from the CORDEX.be initiative (COSMO-CLM and ALARO-0), each spanning a total of 180 years of simulation time. Extreme events were analysed using a threshold-based method based on percentiles for two separate regions with different topography (flatlands vs. hilly region), both at CPS and non-CPS. The research question that we posed was: "Do sub-daily extreme precipitation signals differ between different regional climate models?". We thereby investigated different "signals" of extreme precipitation such as the differences between CPS and non-CPS in relation to regional differences in topography (flat vs. low mountain), daily cycle differences , dependencies of the climate change signal to the rain intensities and differences between the change signal of extremes and seasonal average precipitation.

We found a consistent scale-dependency of the future increase in hourly extreme precipitation for the day-time between both models. For the night-time the scale-dependency was less obvious. For the day-time, COSMO-CLM and ALARO-0 both showed a larger difference in the climate change signal between CPS and non-CPS for extreme precipitation over flatland (Flanders) than for orographically induced extreme precipitation (Ardennes). This result is interesting, since both RCMs are very different (e.g. in terms of model physics land cover parameters and driving GCM) and use very different ways to represent deep convection processes. Despite those model differences, the scale-dependency of projected precipitation extremes is very similar in both models. Our findings therefore suggest that the contrasting scale-dependencies between CPS and non-CPS that were found in previous studies, can be mainly attributed to the characteristics of the region under study (topography and scale) and to a much lesser extent to the specific characteristics of the climate model itself (for example the way deep convective is simulated). However, since other studies in other parts of the world show contrasting results and we only considered two CPMs over one specific region, more similar studies employing other CPMs over topographically-complex regions are needed to generalize our findings. The results also pointed out that the climate change signal is dependent on the rain-intensity that is considered, with generally larger differences between CPS and non-CPS for higher intensities and with generally higher increases in the frequency of the extreme events for the highest-intensity events.

Acknowledgements

The work presented here received funding from the Belgian federal government (Belgian Science Policy Office project BR/143/A2/CORDEX.be) and by the European Research Council (ERC), under Grant Agreement No. 715254 (DRY-2-DRY). The computational resources and services used in this work were provided by the VSC (Flemish Supercomputer Center), funded by the Research Foundation –Flanders (FWO) and the Flemish Government—department EWI. The hourly observational data was provided by VMM (Flemish Environmental Agency). These datasets are available at these institutions upon request. The climate model data used in this study can be requested through the CORDEX.be project website (http://www.euro-cordex.be). Finally, we would especially like to thank Erik Van Meijgaard, for providing us with the EC-EARTH GCM data, and for several constructive discussions.

Supplementary Material

For the evaluation part of this study, we employed hourly precipitation observations from 41 stations in Flanders (Northern half of Belgium), available for the period 2000-2011 and provided by the Flemish Environmental Agency (VMM). Unfortunately, we did not have access to hourly observations for the Ardennes (Southern half of Belgium).

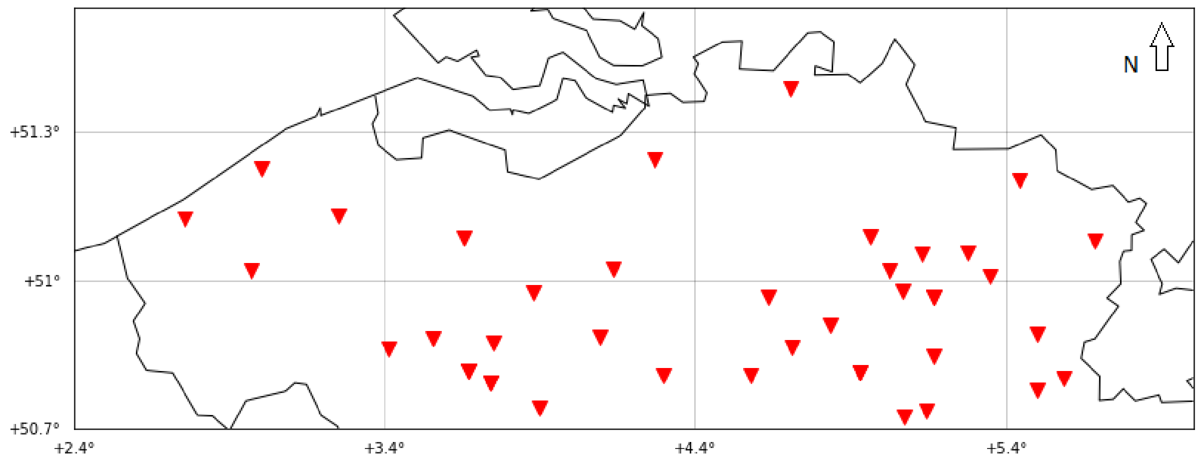

Fig. S1: The 41 hourly observation stations (red triangles) of the VMM, positioned all over Flanders (Northern half of Belgium).

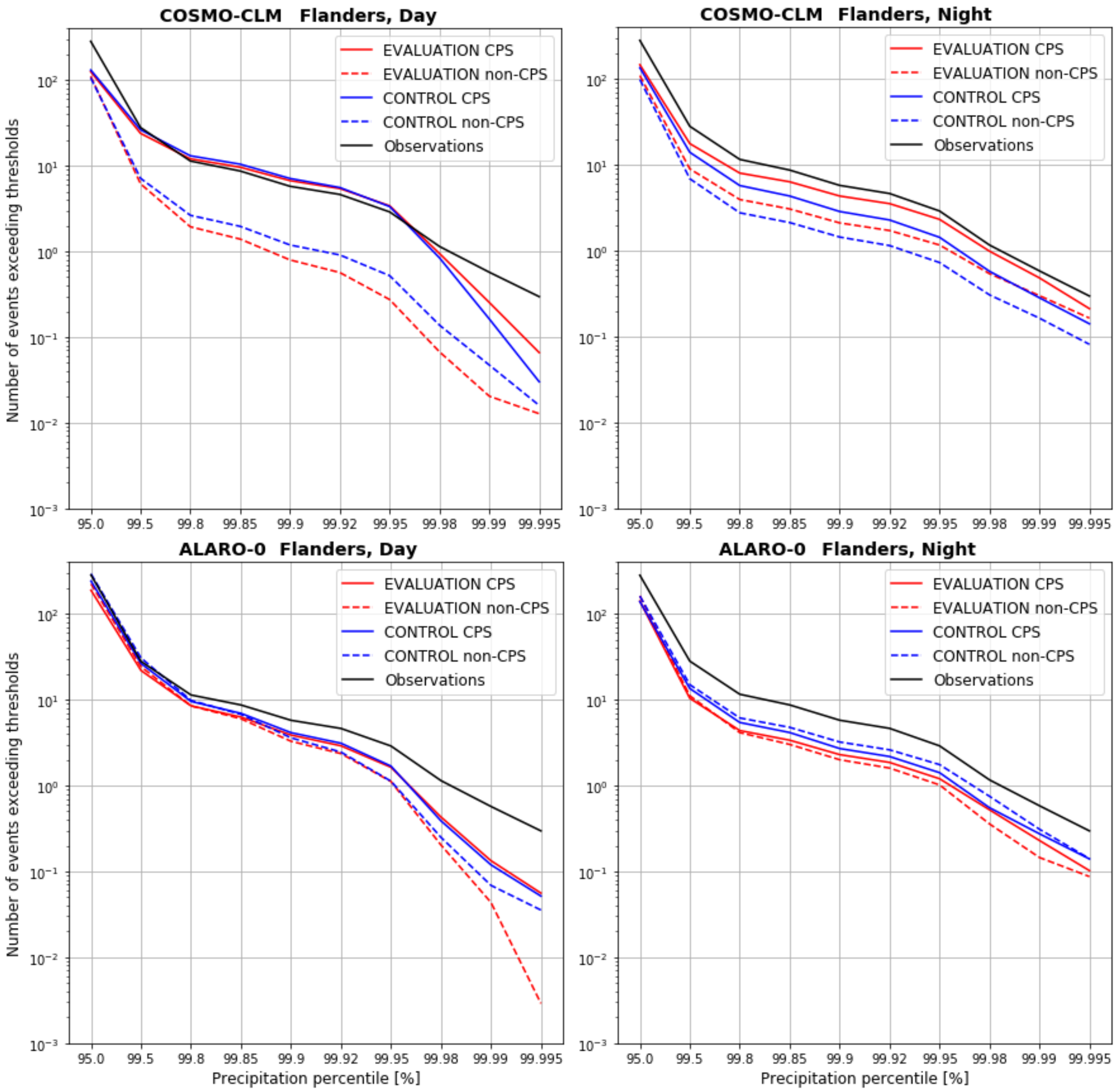

Fig. S2: Present-day summer (JJA) hourly extreme precipitation distributions for Flanders for COSMO-CLM (upper panels) and ALARO-0 (lower panels), for the day-time period (12-18 UTC, left panels) and the night-time period (00-06 UTC, right panels). The distributions are based on the thresholds calculated from the observations. Note that the exceedance numbers (y-axis) are plotted on a logarithmic sale.

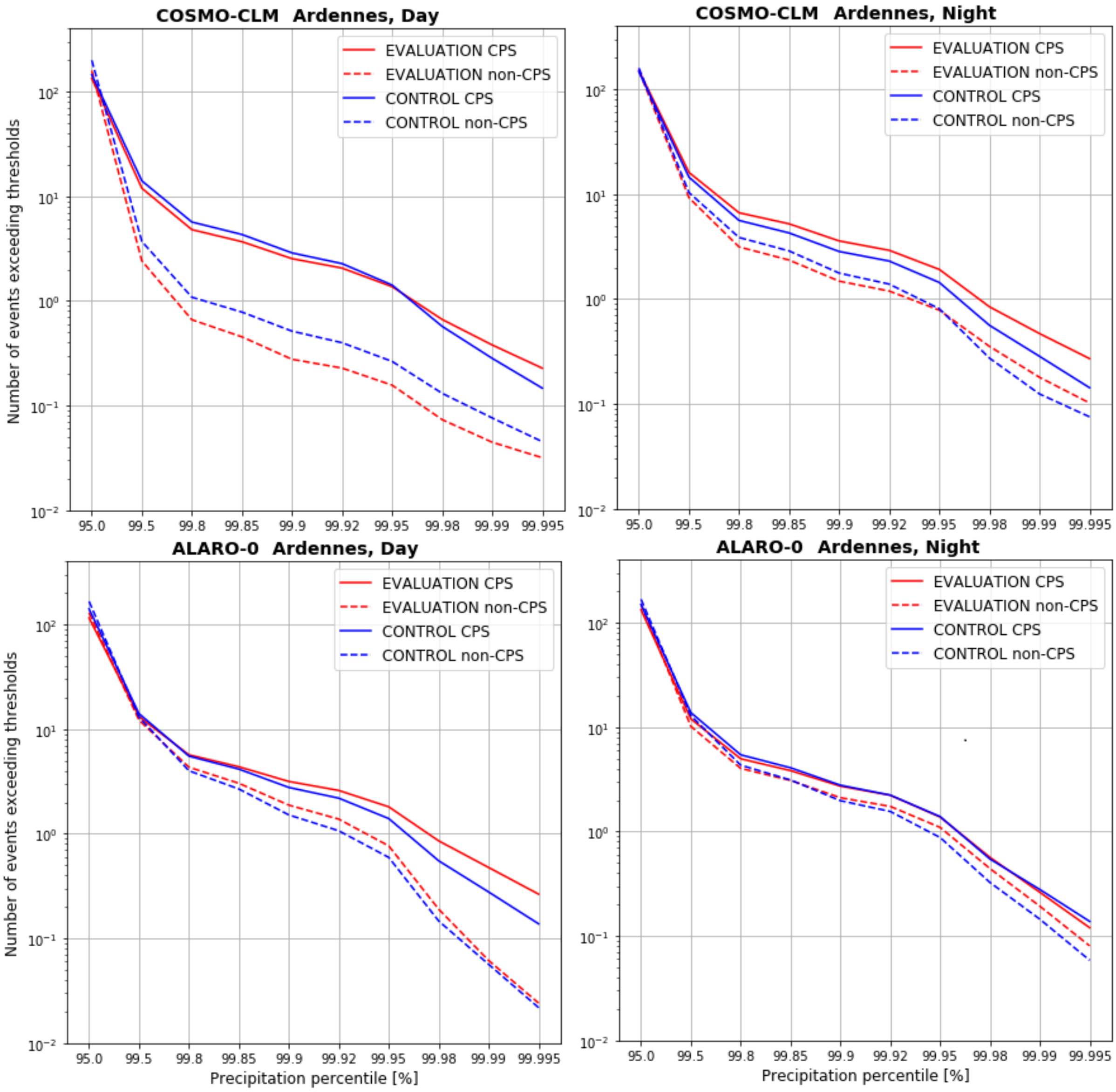

Fig. S3: Present-day summer (JJA) extreme hourly precipitation distributions for the Ardennes for COSMO-CLM (upper panels) and ALARO-0 (lower panels), for the day-time period (12-18 UTC, left panels) and the night-time period (00-06 UTC, right panels). The percentile-thresholds of the CPS simulations were used as reference. Note that the exceedance numbers are plotted on the y-axis on a logarithmic scale.

The spatial pattern of the change in the extreme events exceeding the 99.5th percentile differs considerably between ALARO-0 and COSMO-CLM (Fig. S4). While COSMO-CLM projects a decrease over large parts of the domain, ALARO-0 projects an overall increase. The difference between both models is clearly visible on the difference plots (Fig. S5 c & d). The behaviour of the CPS and non-CPS simulations is similar for both models, which is in accordance with the analyses in Figs 3 and 4. The differences between CPS and non-CPS is also presented in Fig. S5 a & b.

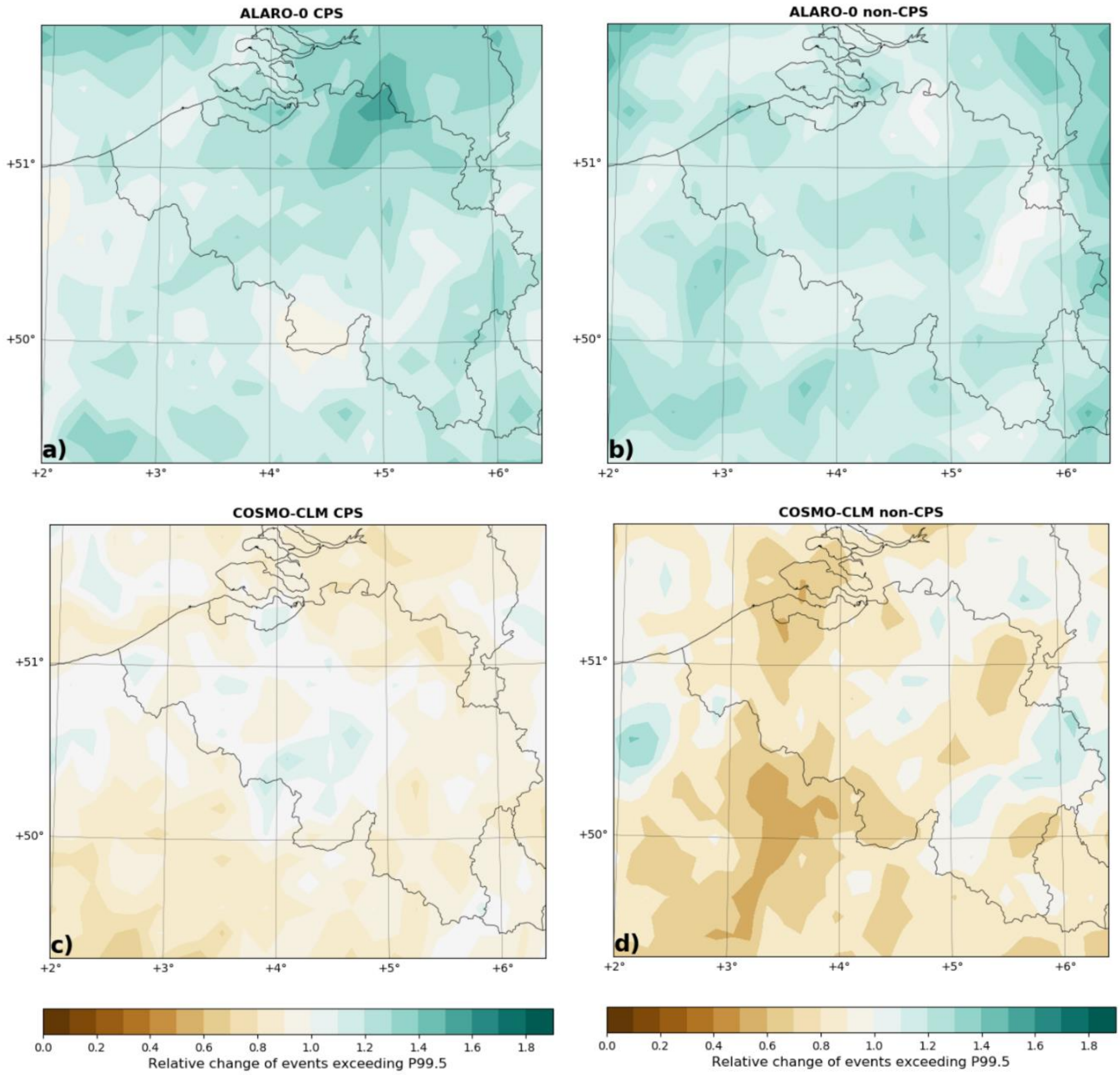

Figure S4: Maps of the end-of-the-century (2070-2100) relative future change (future/present) in the number of events exceeding percentile 99.5 during summer (JJA) for ALARO-0 (top panels, a & b) and 0 COSMO-CLM (lower panels, c & d), at CPS (left panels, a & c) and non-CPS (right panels, b & d). Note that this analysis includes both events during day- (12-18 UTC) and night-time (00-06 UTC).

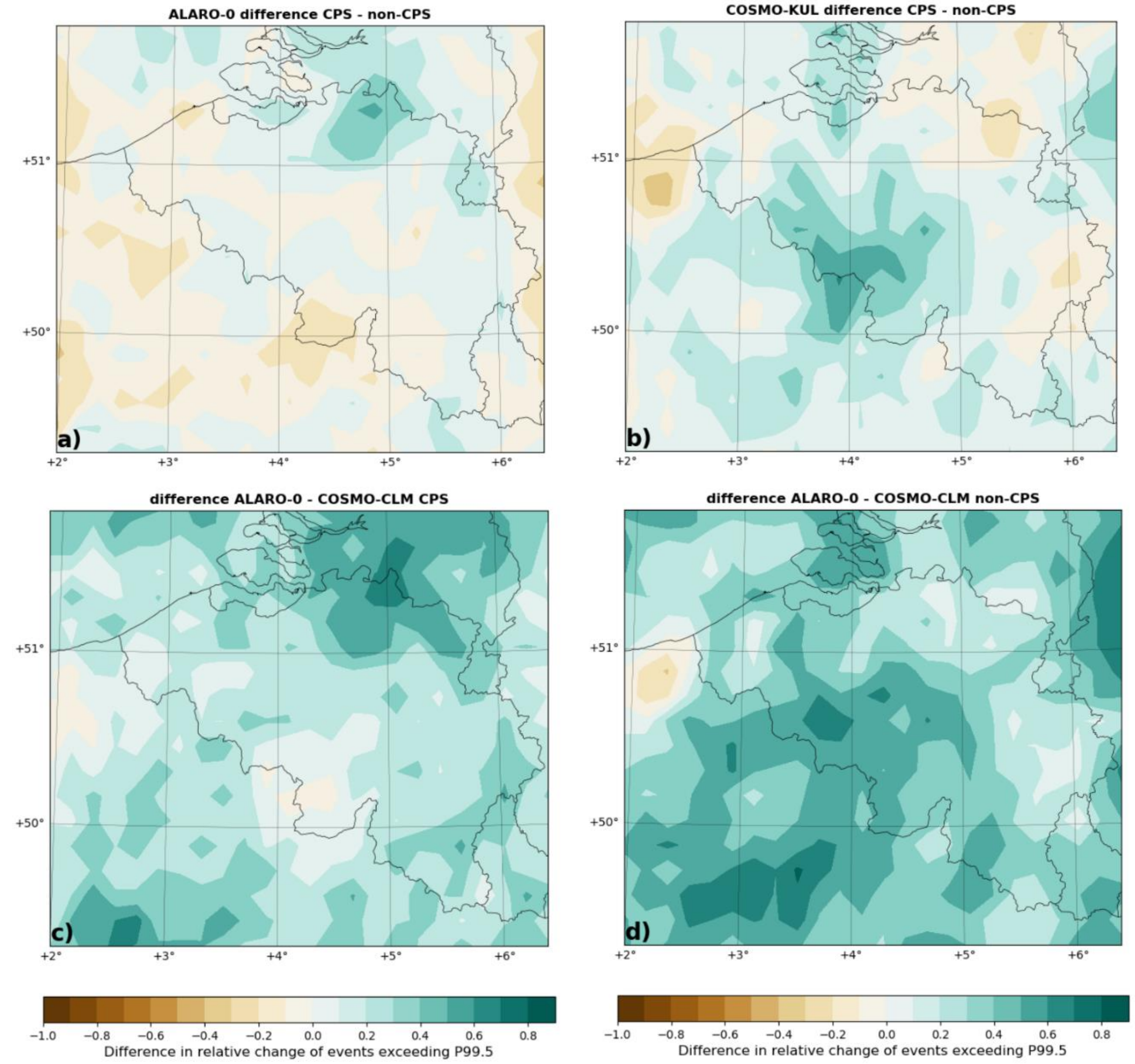

Figure S5: Difference plots between CPS and non-CPS for ALARO-0 (left upper panel, a) and for COSMO-CLM (right upper panel, b) as well as difference plots between ALARO-0 and COSMO-CLM at CPS (lower left panel, c) and at non-CPS (lower right panel, d). The statistic is the change in the number of events exceeding P99.5.

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