Koninklijk Meteorologisch Instituut van België

Institut Royal Météorologique de Belgique

Royal Meteorological Institute of Belgium

Overview of a few regional climate models and climate scenarios for Belgium

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Overview of a few regional climate models and climate scenarios for Belgium

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Contents

Abstract

This report gives a synthetic overview of the recent status of regional climate modelling activities for Belgium performed at three institutions: Royal Meteorological Institute of Belgium (RMI) and the departments of Earth- and Environmental Sciences and Civil Engineering at the Katholieke Universiteit Leuven (KU Leuven). It provides a basis for the coordination and strengthening of the collaboration between the different partners involved in regional climate modelling at the Belgian level in view of creating Belgian climate services. It reinforces the idea that it is beneficial to use the outputs of a wide community of Belgian climate modelling groups and the importance of statistical model output processing is stressed to (a) deal with model biases and (b) to infer the uncertainties that are identified in the outputs of the international model intercomparison projects to the Belgian regional level.

1 Introduction

On 4 April 2014, the Royal Meteorological Institute (RMI) and the Belgian Institute for Space Aeronomy (BISA) organized a stakeholders meeting in the RMI to bring together stakeholders and scientists. The aim was to create a dialogue as a basis for a scientific project to address the needs of the users of climate services. The meeting consisted of a few scientific presentations given by the authors of this report and a panel discussion. During the discussion it became clear that (a) there is an urgent need in Belgium for detailed local regional information and that (b) this information should be delivered in a format that is understandable for the layman and that is easily applicable for decision making.

In this report we do not address the question of how to deliver information and services in a proper format, recognizing that this requires a structural organization such as a Belgian climate center. Here we address the level of details and their related uncertainties of climate-scenario information that could be delivered in future projects.

This report is not meant to be exhaustive; there are other Belgian research groups active in climate modelling, doing excellent research. Decision making should take into account the reliability of the underlying climate information. In climate science this is done by taking into account the information present in large model ensembles. For this reason, creating a wide climate modelling community would be a necessary basis for creating Belgian climate services. The results reported here are limited to activities carried out in the context of past BELSPO projects, in particular the MACCBET project and from some updates of the works carried out in the past CCI-HYDR project, as well as in-kind RMI work.

This year, the contribution of the *Climate Change 2013: The Physical Science Basis* to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) was publised by its Working Group I (WG I). This report gives a comprehensive overview of the current status of climate science to understand the present and past climate, but also to project the future climate change. The latter is important for decision making and can only be carried out by models of various types. This Assessment Report focuses mostly on global scale climate change, synthesizing the outcomes of the large ensemble of global General Circulation Models (GCMs) used in the Coupled Model Intercomparison Projects, in particular the former Phase 3 (CMIP3) and the more recent Phase 5 (CMIP5) (Meehl et al., 2007).

The resolutions of the models in the CMIP experiments are typically of the order of 1 to 2 degrees (about 100-200 km). This imposes limits in the details of the climate information originating from the limitations of the current available computing resources. Such resolutions are very coarse for regional studies in Belgium. By restricting the models to limited areas one can run them at higher resolutions for similar computing costs as global models. This is done by using the data of the global climate models at the lateral boundaries of the limited domains, with a technique that is called *downscaling*. A similar experiment as the CMIP experiments is now carried out in the Coordinated Regional Downscaling EXperiment (CORDEX), see http://wcrp-cordex.ipsl.jussieu.fr/ for further information. In this experiment, regional climate model (RCMs) are run on common domains with resolutions of 50, 25 and 12 km and submitted to a common archive to be made available for further study. For these runs the boundary data of the GCMs of CMIP5 are used and their radiative forcings (i.e. the response to the increases of the greenhouse gases for the next century) follow the Representative Concentration Pathways (RCPs), introduced in the Fifth Assessment IPCC Report.

However, a few Belgian research groups have been running regional climate models with so-called convection permitting resolutions of the order of a few kilometers. There are a few climate applications that benefit from such high resolutions. For instance, such data have been used to study the detailed effect of the Urban Heat Island (UHI) in Brussels (Hamdi et al., 2014) and Antwerp (Wouters et al., 2012). Another example that will be explicitly mentioned in section 4 is the design and planning of sewer systems where precipitation data of very high temporal and spatial resolution is needed. In addition, it is fair to say that with the current resolutions of the Belgian regional climate models we are modelling beyond the maximum resolution of 12 km of the CORDEX experiment.

Going to the convection-permitting scales is not only a matter of increasing the resolution. Modelling at these resolutions also requires a special care for the underlying physics parameterizations of the models. For instance, extra care should be taken of the microphysics and cloud schemes. In that sense there has been some build up of expertise in Belgium of atmospheric modelling at these scales. This leads to a threefold challenge in the roadmap to position the Belgian climate-modelling activities: (i) to consolidate the expertise that was built during the past decade and (ii) to capitalize on the high-resolution climate modelling tools to produce highly detailed climate information for future Belgian climate-information end users, and (iii) to position these high-resolution runs with respect to the model runs carried out within the CORDEX project. This report does not address the Belgian contributions to CORDEX, but offers an idea of what can be delivered at the very detailed regional scale.

This report is organized as follows. In section 2 the regional climate model ALARO of the RMI will be described together with a first scenario output that was computed based on the A1B scenario of the Fourth IPCC Assessment Report. In section 3 a brief overview will be given of the modelling activities with the COSMO-CLM model at the Department of Earth and Environmental Sciences at the KU Leuven. In section 4 it will then be explained that statistical treatments of model output is necessary, an expertise that is present at the Department of Civil Engineering of the KU Leuven. Some recent work in this domain will be presented that demonstrates its potential to process the output of the Belgian RCMs and the ones generated by the CMIP and the CORDEX projects. Some conclusions can be drawn from this recent work and they will be presented in section 5. These conclusions are pertinent for facilitating the creation of Belgian climate services.

2 Regional climate modelling at the Royal Meteorological Institute of Belgium

2.1 Model description

The Royal Meteorological Institute of Belgium (RMI) uses its own atmospheric model which is used operationally for the daily weather predictions as well as for climate studies. This model is the ALADIN model which is the limited area model (LAM) version of the ARPEGE-IFS forecast system (Bubnová et al., 1995; ALADIN international team, 1997) (Fig. 1 (a)-(b)). Since the 1990s the model has been widely used in the numerical weather prediction (NWP) community and, more recently, the model is also used for regional climate modelling (e.g. Radu et al., 2008; Skalák et al., 2008). Updates of physical parameterizations within the ALADIN model have recently resulted in a new version of the model, the so-called ALARO-0 model. The new physical parameterizations within the ALARO-0 model as proposed by Gerard et al. (2009), were specifically designed to be used from the mesoscale to the convection permitting scales (so-called 'grey-zone' scales) and are centered around an improved convection and cloud scheme.

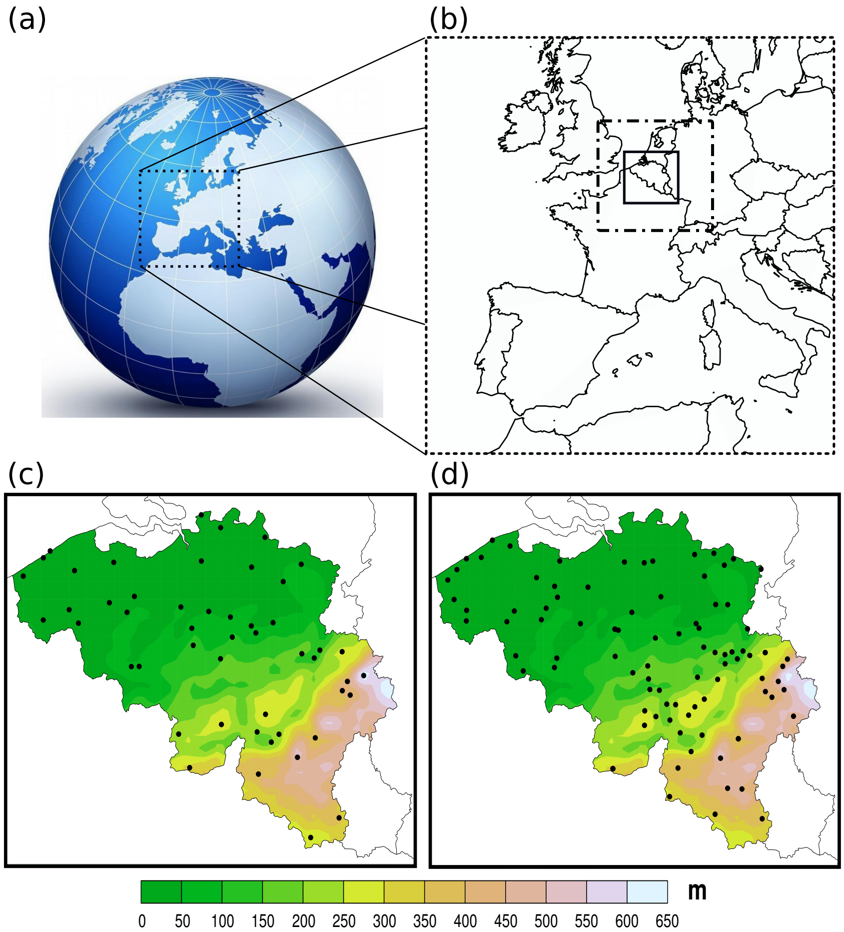


Figure 1: (a) Global model domain of Arpège/ERA-40; (b) Limited area model domain of the ALADIN or ALARO-0 model at 40 km resolution (dashed line) and the ALARO-0 model at 4 km resolution (dashed-dotted line); (c)-(d) Zoom on Belgium of the ALARO-0 model at 4 km resolution. The colors show the topography of Belgium (m) and the black dots indicate the locations of the 93 and 50 climatological stations which are used for the validation of summer precipitation and summer maximum temperature, respectively.

2.2 Model performance

Model validation for the recent past climate is a first and necessary step before these models can be used for confident future climate projections. The climate modelling research group of the RMI has begun to perform such validation studies. In these studies the two main meteorological variables temperature and precipitation from the ALADIN- and ALARO-0 model at different spatial resolutions have been compared with respect to observations. Convective processes, which are characterized by intense and scattered showers as well as high temperatures, mainly occur during the summer. Therefore, the climatology of the ALADIN- and ALARO-0 model - the latter including the new physics parameterizations for deep convection and clouds - have been tested for Belgium for a 30-year *summer* period (1961-1990) (Hamdi et al., 2012; De Troch et al., 2013).

The experimental design consisted of a dynamical downscaling of the ERA-40 reanalysis (Uppala et al., 2005) from the European Centre for Medium-Range Weather Forecasts (ECMWF) with daily reinitializations using a one-way nesting approach. The output from this downscaling, using the ALADIN- and ALARO-0 model, has been validated by comparing the model data with respect to observations from the climatological network of the RMI. For the validation period 1961-1990, 50 and 93 climatological stations have been selected for temperature and precipitation respectively (Fig. 1 (c)-(d)). Different simulations for the recent past climate have been evaluated: (i) a simulation at a spatial resolution of 40 km using the ERA-40 reanalysis as boundary conditions and (ii) two simulations at a resolution of 10 km and 4 km spatial resolution using the output from the 40 km simulation at the boundaries. The simulation at 4 km spatial resolution have only been performed with the ALARO-0 model since the old paramaterizations within the ALADIN model cannot be applied at such high resolutions (see Table 1).

Table 1: Experimental design

		ALADIN		**ALARO-0**		
Validation	Resolution	40 km	10 km	40 km	10 km	4 km
	Acronym	ALD40	ALD10	ALR40	ALR10	ALR04
	Boundary conditions	ERA-40	ALD40	ERA-40	ALR40	ALR40
A1B Scenario	Resolution	X	X	40 km	X	4 km
	Acronym	X	X	ALR40	X	ALR04
	Boundary conditions	X	X	ARP	X	ALR40

We limit ourselves here to 2 results from De Troch et al. (2013) and Hamdi et al. (2012). Figure 2 shows the observed and simulated spatial distribution of the 30-year averaged summer precipitation. On top of each sub-figure average values over the 93 stations for the cumulated summer precipitation are given. On average all models overpredict the observed cumulated summer precipitation. Both the observation- and the simulation fields show a clear topographical dependency, with a gradual increase in precipitation going from the northwest (low altitudes) to the southeast (high altitudes) of the country. The ALARO-0 and ALADIN simulation at 40 km show a very similar distribution. Obviously the precipitation fields for the simulations with low spatial resolution are less heterogeneous than the ones with high spatial resolution. For the higher resolution simulations ALARO-0 approaches much better the observations than ALADIN. For instance, ALD10 overpredicts cumulated summer precipitation with values which are in average over all stations almost 100 mm higher than observed. On the contrary, the average values for ALR10 and ALR04 differ only slightly from the observations and also the observed local maximum at the higher altitudes, is very well simulated by both models (De Troch et al., 2013). Figure 3 gives for each station the 5-year return levels of daily summer maximum temperature between 1961-1990 obtained from the observations, ALD40, ALD10 and ALR04. It can be clearly seen that ALR04 is able to reproduce the observed daily summer maximum temperature corresponding to a return period of 5 years, while the other models significantly fail to reproduce the extreme-value statistics (Hamdi et al., 2012).

So the ALARO-0 model outperforms the old ALADIN model of the RMI, specifically for impact studies of extreme precipitation.

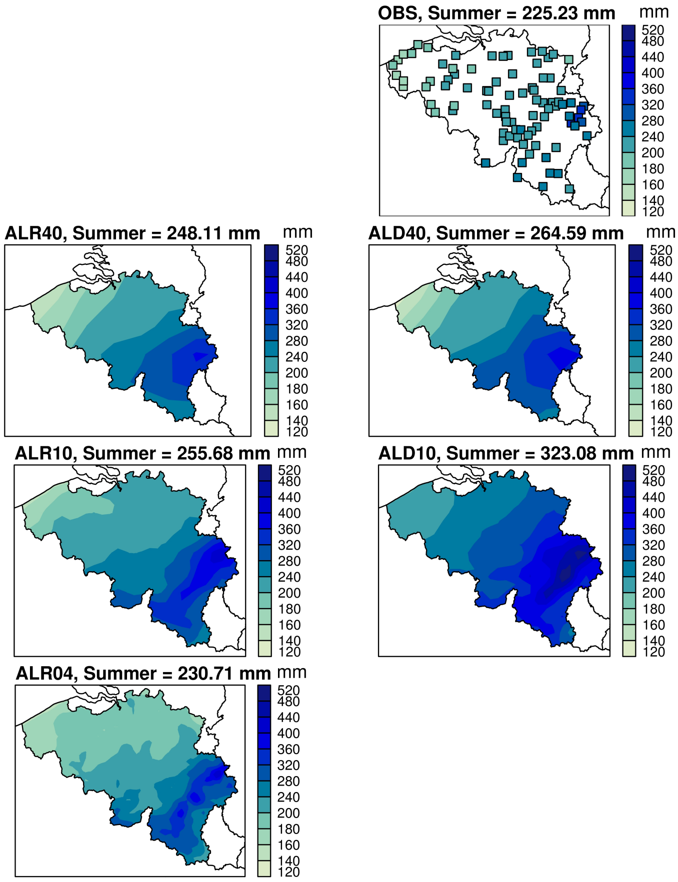


Figure 2: Spatial distribution of 30-year (1961-1990) mean cumulated summer precipitation from observations and model simulations (left: ALR40, ALR10, ALR04; right: Observations, ALD40, ALD10). The mean summer precipitation over the 93 climatological stations is given above each subfigure (Figure adapted from De Troch et al. (2013)).

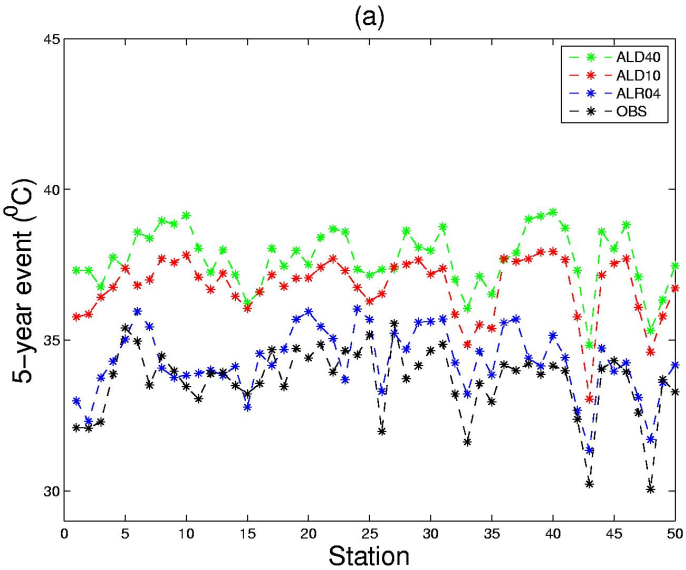
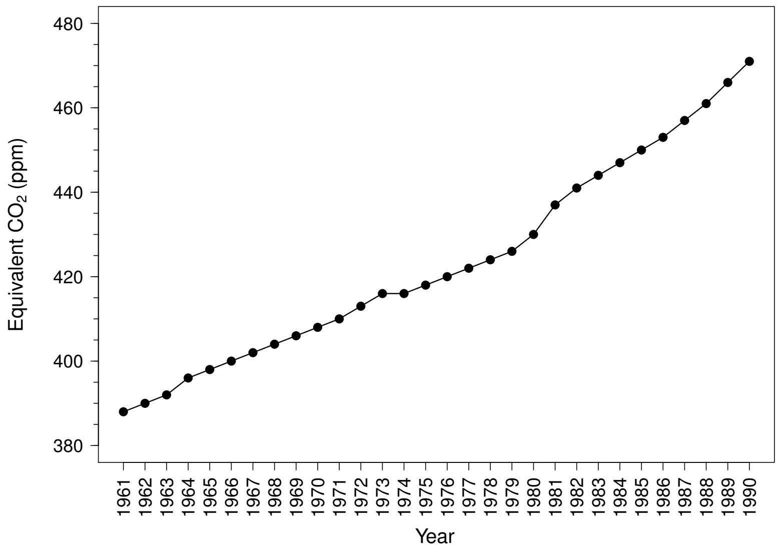


Figure 3: 5-year return event of daily summer maximum temperature in each of the 50 stations from observations and model runs (ALD40, ALD10 and ALR04) (Figure adapted from Hamdi et al. (2012)).

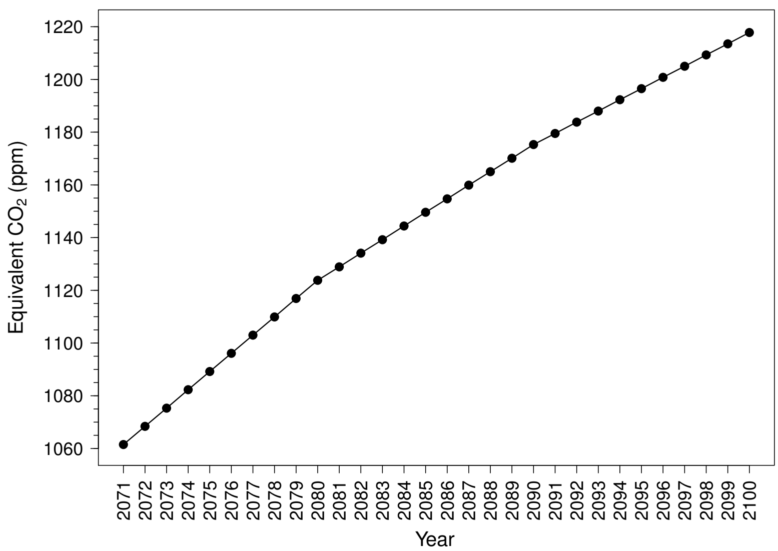
2.3 Climate scenario

The validation of the ALARO-0 model has showed that the model is a good candidate model for regional climate modelling and that it can be used for the computation of future climate scenarios (e.g. Hamdi et al., 2012; De Troch et al., 2013).

The global climate model (GCM) Arpège which is developed by the Centre National de Recherces Météorologiques (CNRM) took part within the Coupled Model Intercomparison Project Phase 3 (CMIP3) (further in the text and figures also denoted as CNRM-CM3). These GCM output from Arpège are dynamically downscaled using ALARO-0 at 40 km horizontal resolution, followed by a one-way nesting where the output from the 40 km simulation is used as boundary conditions to perform a 4 km ALARO-0 simulation on a 181x181 domain centered above Belgium (see Table 1 and Fig. 1 (b)). The simulations are done for a 30-year period from (i) 1961-1990 and (ii) 2071-2100. In the text the present climate (pc) and future climate (fc) experiments will be referred as the *reference* and *scenario* simulation, respectively.



(a) Reference simulation (1961-1990)

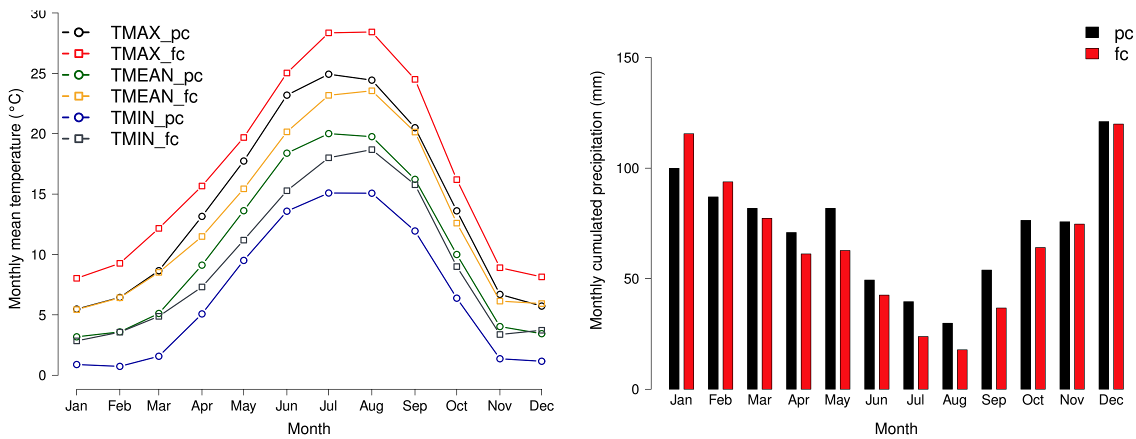


(b) Scenario simulation (2071-2099)

Figure 4: Values for equivalent CO_2 corresponding to the A1B scenario.

A realistic approach is to consider the transient climate response (TCR) associated with a transient increase based on expected emission scenarios. IPCC has defined “emission scenarios” for future changes in the greenhouse gas (GHG) concentrations which are dependent on different economic evolutions as well as on evolutions in decision making and policy. Therefore, in order to quantify the sensitivity of the climate to external forcings we have modified the amount of equivalent CO_2 in the model according to the IPCC emission scenario A1B. The equivalent CO_2 is the concentration of CO_2 that would cause the same amount of radiative forcing as a given mixture of CO_2 and other greenhouse gases (Baede, 2007). Figure 4 shows the equivalent CO_2 values according to the A1B scenario as used for the reference and scenario simulation (Fig. 4(a) and 4(b), respectively). The A1B scenario describes a future world of very rapid economic growth and the rapid introduction of new and more efficient technologies. This scenario assumes a “balance“ across all energy sources, i.e. not relying too heavily on one particular energy source (http://www.ipcc.ch/ipccreports/tar/wg1/029.htm). The results from these present and future climate simulations are described below, showing the changes in monthly, seasonal and extreme temperature and precipitation.

Figure 5 demonstrates the 30-year average monthly mean temperature fields (maximum-, mean-, and minimum temperature, Fig. 5(a)) and monthly mean precipitation (Fig. 5(b)) for the present- (pc) and future climate (fc), respectively. The climatology is clearly visible in the monthly distributions for both the reference and scenario simulation. For temperature the monthly values are systematically higher for fc than for pc. The differences are largest during the months July to September for all three temperature variables (maximum-, mean- and minimum temperature). All months except for the wintermonths (December, January, February) show a consistent decrease in monthly precipitation for fc.

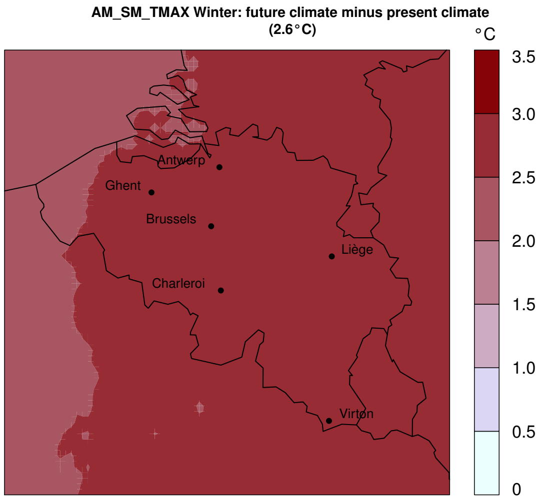


(a) (b)

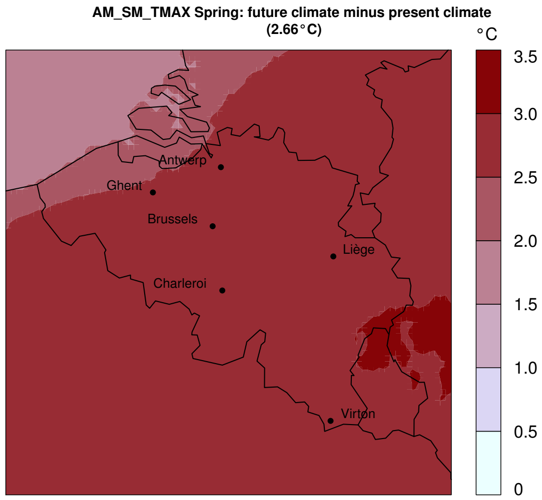
Figure 5: 30-year average monthly monthly mean temperature (a) and cumulated precipitation (b) for the present- (pc) and future climate (fc), respectively.

Figure 6 and 7 show the 30-year (2071-2100) seasonal mean anomaly relative to the 30-year mean for the period 1961-1990 for maximum temperature and precipitation. The maximum temperature fields (Fig. 6) show consistently positive differences throughout all seasons. For all seasons the differences are smaller in the coastal region than in the rest of the country. This gradual distribution persists throughout the seasons and becomes most pronounced during the summer showing a clear increase in anomalies going from the northwest to the south of the country. Furthermore, the increase in maximum temperature during summer correspond on average to 3.08 °C.

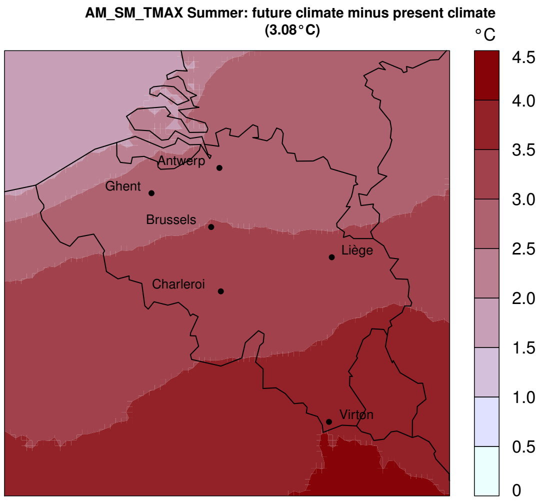
Except for the winter season, the precipitation field shows for all seasons a decrease in precipitation throughout the whole country (Fig. 7(a)). Similarly to the summer maximum temperature field, the summer precipitation shows a gradual increase in negative differences going from the northwest to the south of the country. For the winter are throughout the whole country positive differences visible, with an average increase in winter precipitation of 21.31 mm.



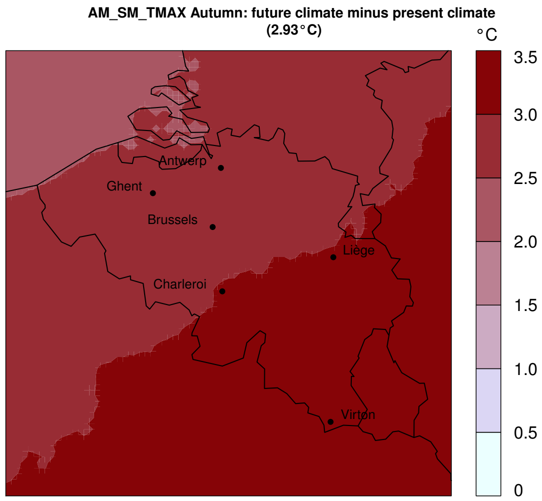
(a) Change in winter maximum temperature



(b) Change in spring maximum temperature

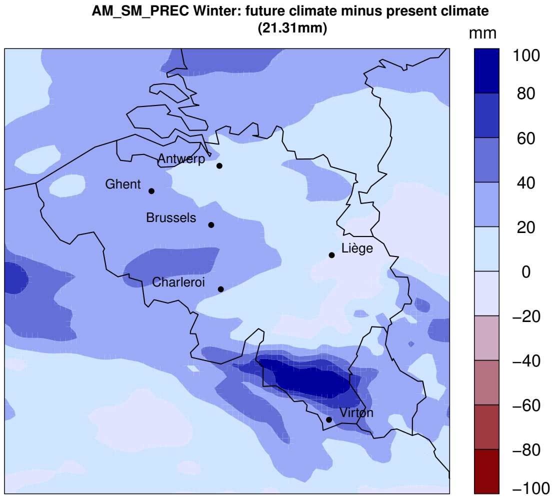


(c) Change in summer maximum temperature

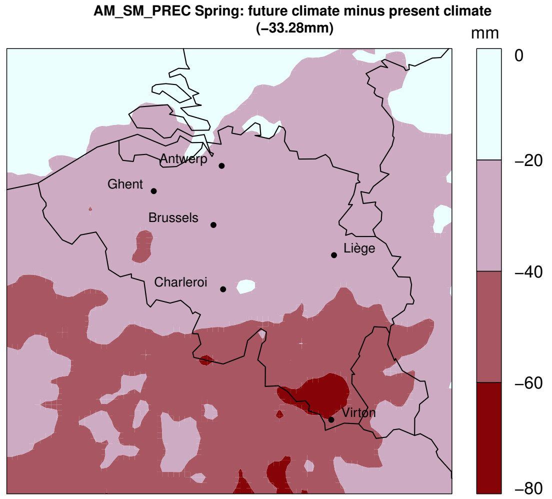


(d) Change in autumn maximum temperature

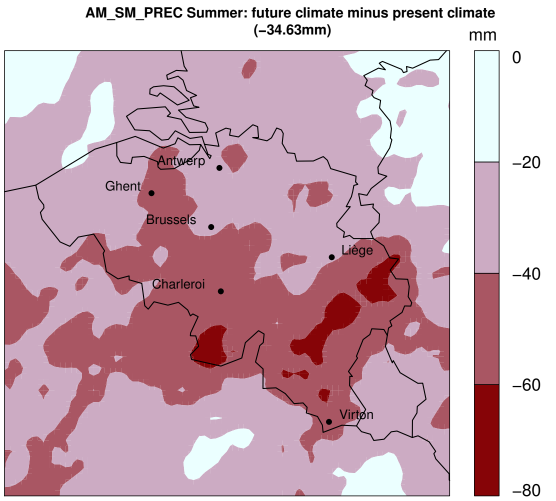
Figure 6: 30-year (2071-2100) seasonal mean anomaly relative to the 30-year mean for the period 1961-1990 for maximum temperature.



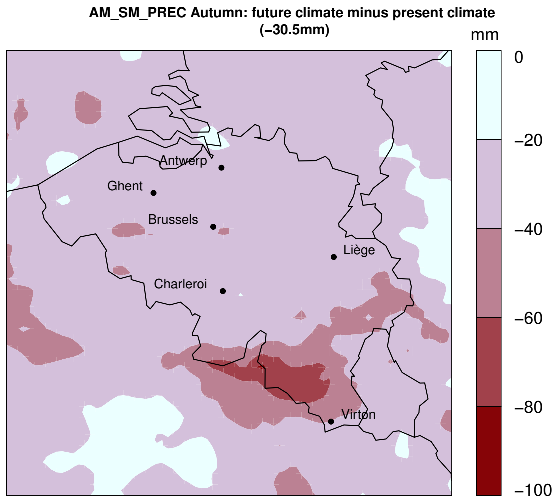
(a) Change in winter precipitation



(b) Change in spring precipitation



(c) Change in summer precipitation



(d) Change in autumn precipitation

Figure 7: 30-year (2071-2100) seasonal mean anomaly relative to the 30-year mean for the period 1961-1990 for precipitation.

To study the changes in extreme temperature and precipitation, frequencies have been calculated. For maximum temperature (precipitation) daily absolute frequencies have been calculated from 30-year (pc and fc) winter, spring, summer and autumn daily maximum temperature values (precipitation) which are binned into bins of 1 °C (precipitation, first bin: 0-1 mm day^{-1}, next bins have binsize of 5 mm day^{-1}). A logarithmic scale has been used for better representation of the extreme values. The frequencies are computed for all gridpoints that coincide with Belgium (i.e. subregion of 81x81 gridpoints, Fig. 1 (c)-(d)). The bottom panels of Fig. 8 show the relative differences between fc and pc frequencies ((fc-pc)/pc). The frequencies for maximum temperature show for all seasons a clear shift to higher temperature values for the fc. This shift clearly occurs both at mean temperature values as well as at the tails of the distribution (i.e. extremes). For precipitation there are only changes in the frequency distribution visible for winter (Fig. 9(a)). A slight decrease in dry days for fc is visible, while for the higher precipitation amounts ranging between 20 and 100 mm day^{-1}, the frequencies in winter precipitation are higher for fc than for pc.

In conclusion, the results presented in this section demonstrate that the downscaling of global Arpège data (CNRM-CM3) using the ALARO-0 4-km resolution model with adapted values for equivalent CO_2 allows to study climate sensitivity.

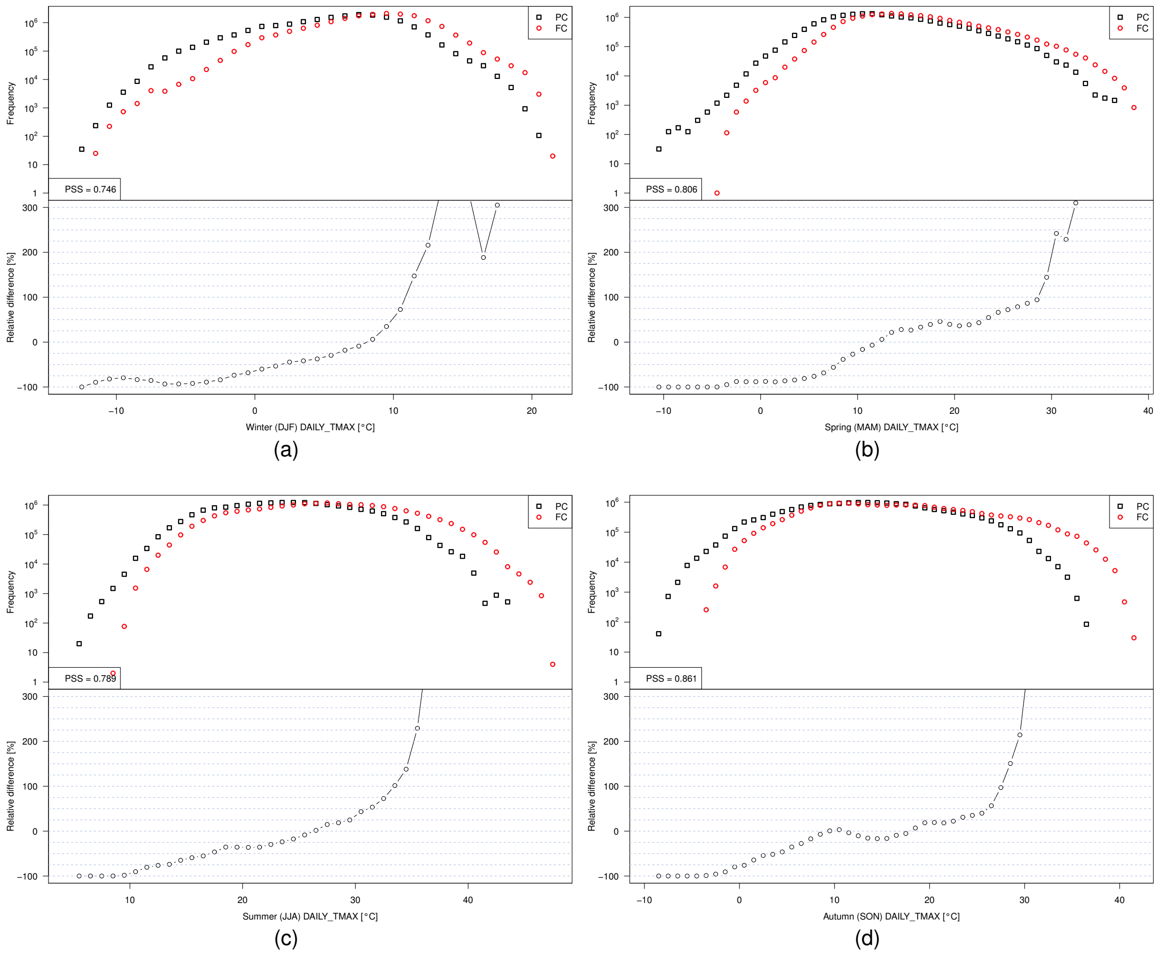


Figure 8: Relative frequencies of 30-year (pc; 1961-1990 and fc; 2071-2099) daily maximum temperature from winter (a), spring (b), summer (c) and autumn (d). The frequencies are displayed on a logarithmic scale.

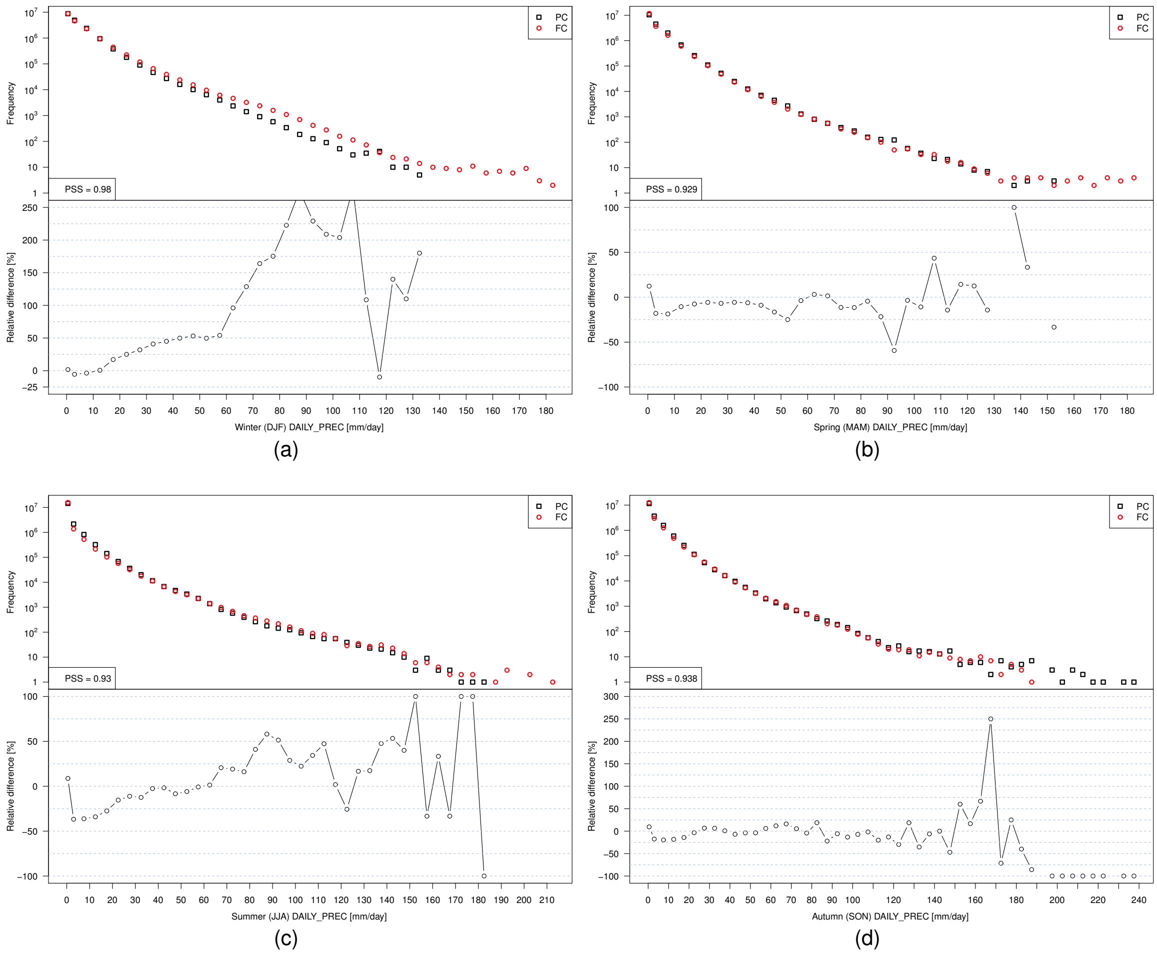


Figure 9: Relative frequencies of 30-year (pc; 1961-1990 and fc; 2071-2099) daily cumulated precipitation from winter (a), spring (b), summer (c) and autumn (d). The frequencies are displayed on a logarithmic scale.

3 Regional climate modelling at the department of Earth- and Environmental Sciences of KU Leuven

3.1 Model description

The regional climate modelling group in the department of Earth and Environmental Sciences of KU Leuven uses the COSMO-CLM regional climate model developed by the Deutsche Wetterdienst (DWD). The COSMO-CLM model is a non-hydrostatic climate limited area model. This model is based on the COSMO model (Steppeler et al., 2003), designed by DWD for operational weather prediction on the meso-β and meso-γ scales. In order to perform climate integrations with the COSMO model, the climate limited-area modelling (CLM) community provided extensions such as dynamic surface boundaries, a more complex soil model or the possibility to use various CO_2 concentration values (Böhm et al., 2006). A detailed description of the COSMO-CLM (CCLM) can be found on http://www.clm-community.eu/index.php?menuid=17. The climate modelling group at the department of Earth and Environmental Sciences, KU Leuven performed several very high resolution climate simulations over Belgium using CCLM. A list of the climate simulations performed in KU Leuven is listed in Table 2, where ERA-Interim is a more recent version of the ERA-40 reanalysis experiment of the European Centre for Medium Range Weather Forecasts (ECMWF) and where EC Earth is a version of the Integrated Forecast System (IFS) of the ECMWF used as a General Circulation Model (GCM) for global climate simulations in the CMIP5 project. Runs with the Representative Concentration Pathways (RCP) for both the $4.5W/m^2$ and the $8.5W/m^2$ radiative forecings were carried out. For all simulations, the first year is considered as spin-up, resulting in 11-year study periods.

Table 2: List of high resolution simulations performed at KU Leuven using CCLM

	Boundary Conditions	CCLM Spatial Resolutions	Period
1	ERA-Interim	25 km, 7 km, 2.8 km	1999-2010
2	EC-Earth (RCP4.5)	Same as above	1999-2010
3	EC-Earth (RCP4.5)	Same as above	2024-2035
4	EC-Earth (RCP4.5)	Same as above	2059-2069
5	EC-Earth (RCP8.5)	Same as above	2059-2069

3.2 CCLM performance over Belgium

It is important to evaluate a regional climate model before using it for climate studies over a particular region. For this purpose the climate modelling group at KU Leuven performed very high resolution (2.8 km) climate simulations for present day (1999-2010) climate using ERA-Interim boundary conditions. A 3-steps nesting approach has been applied. The driving data is nested in a 100x100 gridpoints domain with a 0.22°(25 km) grid mesh size. The resulting three hourly outputs are nested in a 0.0625°(7 km) domain. During this nesting step hourly outputs are produced on a 150x150 gridpoints domain. Finally, the 0.025°(2.8 km) convective permitting simulation (CPS) is produced on a 192x175 domain. The three nests allow the assessment of the added values of an increase in resolution from two non-CPS to a CPS simulation. When comparing a CPS to a non-CPS, it is therefore easier to assess the sources of possible improvement, namely the increase in resolution or the use of dynamical resolved deep convection. It was therefore decided to perform the simulations through a 3-step nesting strategy. The differences occurring at different model resolutions are also assessed.

Figure 10 shows the three nested model domains. The evaluation is performed over Belgium for the three nested grids. A gridded European observation dataset (EOBS) version 7.0 is used for the evaluation (Haylock et al., 2008). Additionally we also employed precipitation and temperature data from the Royal Meteorological Institute (RMI) of Belgium and from the Global Historical Climatology Network-Daily (GHCND) dataset (Menne et al., 2012). Only stations covering the full simulation period (2000-2010) are used, resulting in 199 stations. We also used hourly precipitation values derived from the Vlaamse Milieumaatschappij (VMM) dataset. The main evaluation has been performed for different variables such as temperature, precipitation, wind, clouds, radiations etc. However, here we show only the results for temperature and precipitation over Belgium using the EOBS dataset as a reference.

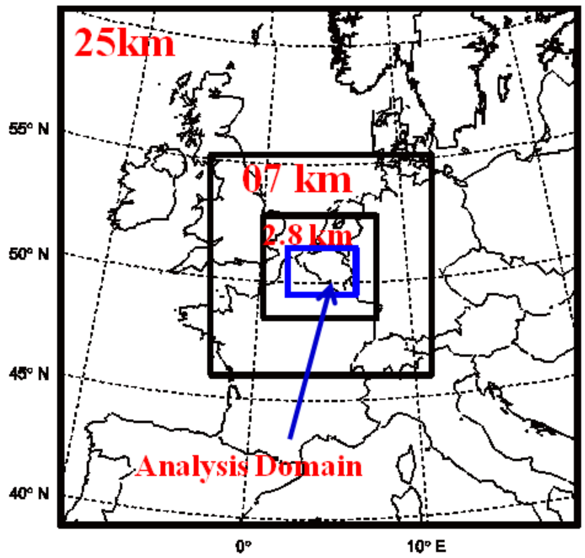


Figure 10: Model domains used for the 3-steps nesting (25km, 7 km, 2.8km). The analysis domain (blue) coincides with Belgium.

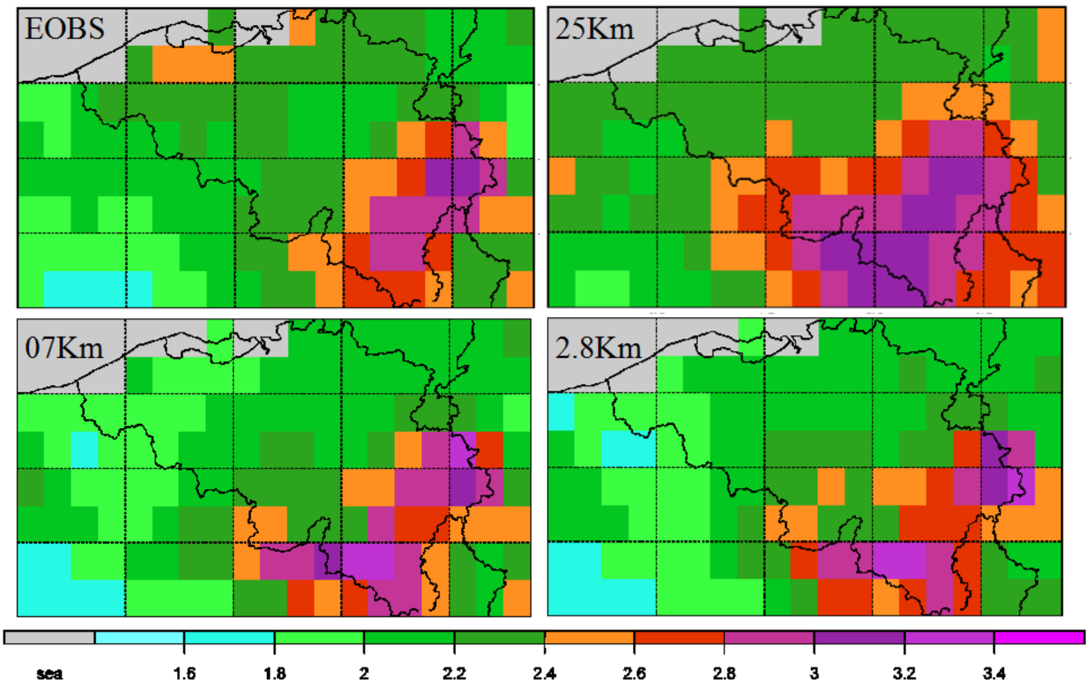
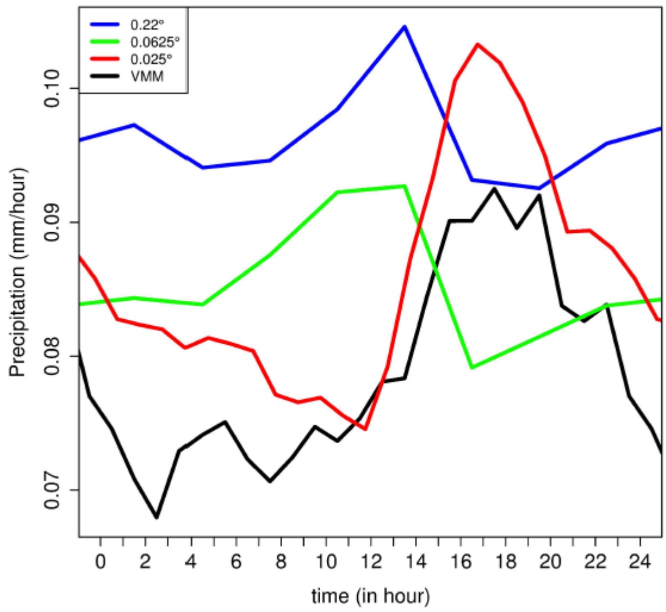
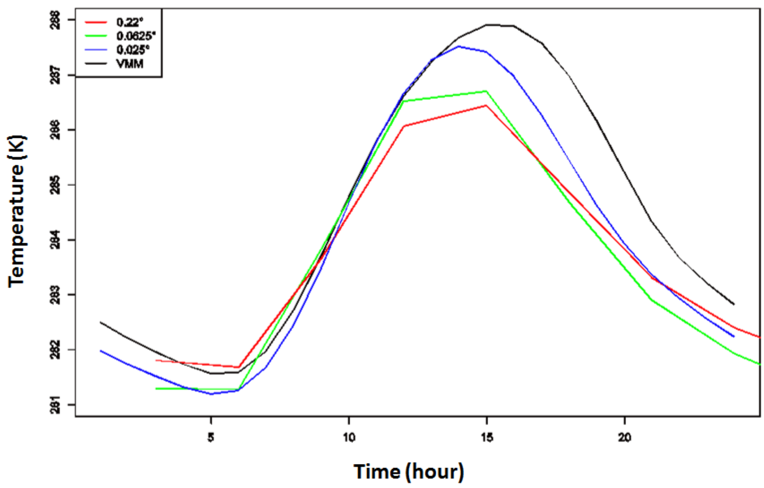


Figure 11: Observed and simulated mean annual precipitation over Belgium for present day climate (2000-2010). The three different resolutions are shown in the upper left corner of the plots. In this case CCLM is driven with ERA-Interim boundary conditions.

Figure 11 shows the observed and simulated mean annual precipitation over Belgium for the period 2000-2010. Observations show enhanced (reduced) precipitation over the eastern (western) part of the domain. In the hilly areas the observed precipitation reaches 3.4 mm day^{-1}. In general, the model reproduces fairly well the precipitation range over Belgium in all three simulations. The spatial extend of the area with enhanced precipitation is overestimated in the coarser simulation (25 km). The coarse description of orography in this simulation is likely to be responsible for this overestimation. Indeed the refinement of orography in the 7 km and 2.8 km model simulations leads to a more realistic simulation of the spatial pattern of precipitation over Belgium. Another benefit of the increased resolution is the better simulation of the timing of the deep convection that allows an improvement in the daily precipitation cycle (Fig. 12(a)).



(a)



(b)

Figure 12: CCLM daily precipitation cycle (a) and temperature cycle (b) over Belgium for the three resolutions (0.22°/ 25 km, 0.0625°/ 7 km, 0.025°/ 2.8 km) compared to the observations (indicated by VMM).

On the other hand the observed 2m-temperature shows increased (decreased) annual mean values over the western (eastern) parts of the domain (Fig. 13). CCLM fairly reproduces the spatial pattern of the temperature over Belgium. Compared to the non-CPS simulations we found an improvement in the daily temperature cycle over Belgium in the CPS simulation (Fig. 12(b)). Note that the different position of the temperature curves is due to the different temporal resolution that is used for producing output (every 15 minutes for the 0.025°simulation, 3-hourly for the 0.0625°and 0.22°simulations). In almost all cases (non-CPS, and CPS) the CCLM underestimates the observed temperature by 0.5 K in most part of the domain. However, the model overestimates the mean annual 2m-temperature over Kortijk and surrounding regions in all three simulations. This overestimation becomes larger in the CPS simulation. A similar bias has been observed when CCLM is driven with EC-Earth boundary conditions (not shown here). Further investigations are therefore needed to examine the reason for this overestimation.

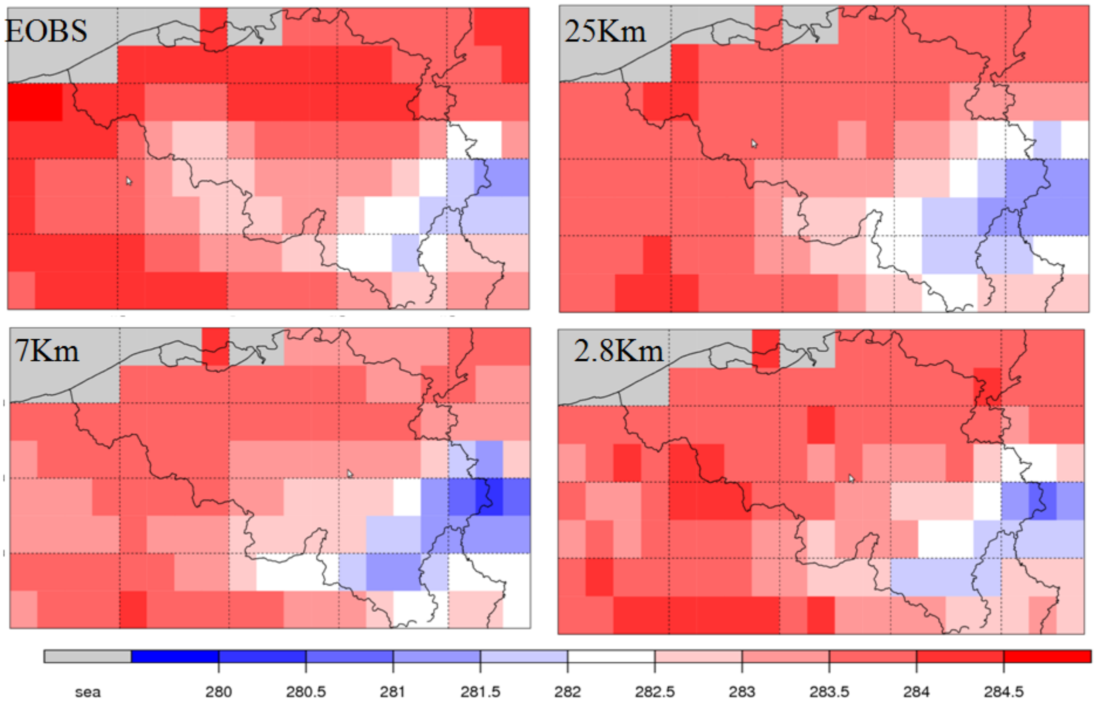


Figure 13: Observed and simulated mean annual 2m-temperature (in Kelvin) over Belgium for present day climate (2000-2010). The different resolutions are shown in the upper left corner of the plots. In this case CCLM is driven with ERA-Interim boundary conditions.

3.3 Future climate simulation

In the next step we carried out simulations for the present-day and future climate using global climate model data as driving data. The EC-Earth (Hazeleger et al., 2010) boundary conditions are used to perform the simulations for the present-day and future climate respectively (Table 2). In the GCM driven simulations, historical levels of greenhouse gases are used for the period 2000-2005, and for the periods thereafter RCP4.5 and RCP8.5 concentrations are used for the resp. two scenarios.The CCLM simulated precipitation over Belgium using EC Earth boundary conditions for the present day climate (2000-2010) show similar features as the ERA-Interim driven runs. Although present-day climate shares similar statistical properties as the observed climate, the day-to-day meteorology differs (not shown). Similar to the ERA-Interim driven simulation the precipitation and temperature biases are improved at higher resolution (2.8 km run).

The climate sensitivity is derived by comparing the near future simulation with the present day simulation. Here we show only the 2m-temperature changes for the near future in the CPS simulation. Figure 14 shows the spatial distribution of 2m-temperature between near future (2025-2035) and present day climate (2000-2010) over Belgium. A climate change signal is apparent, showing a warming throughout the whole country in the near future. The 2m-temperature change ranges between 0.85 K and 0.95 K over Belgium. Further analysis of the 2m-temperature reveals an increased number/frequency of hot days in the near future (Fig. 15). The uncertainty in the above results associated with the short simulation periods and single realization cannot be ignored.

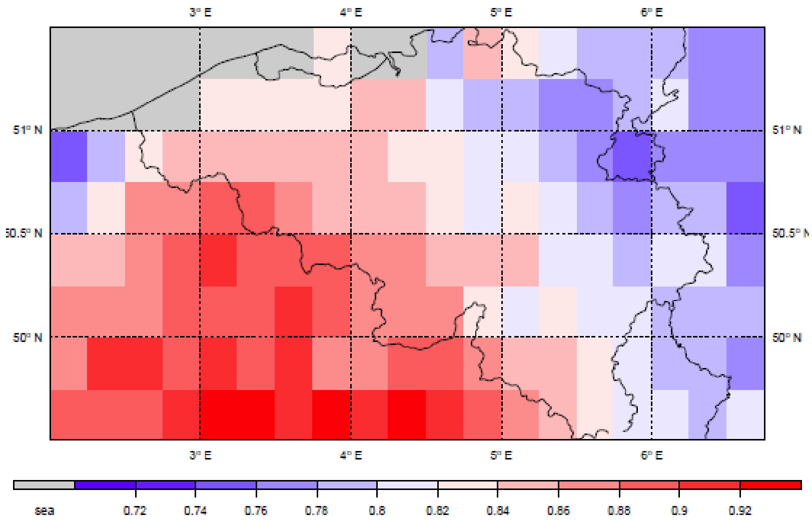


Figure 14: The difference of the 2m-temperature between the near future (2025-2035) and present day climate (2000-2010) over Belgium in the CPS simulation. CCLM is driven using RCP4.5 EC-Earth boundary conditions.

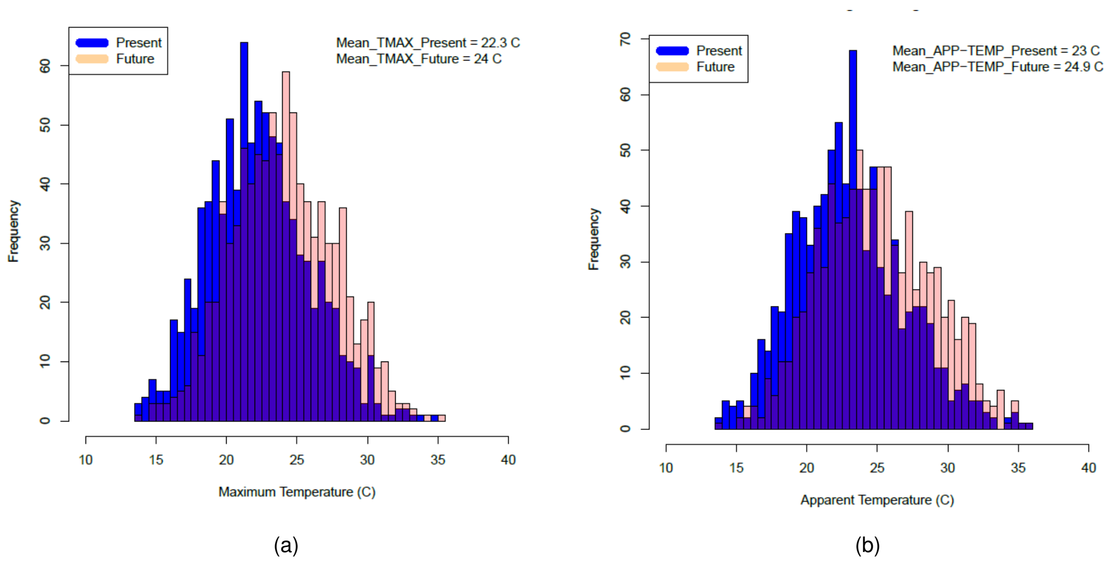


Figure 15: Histogram of simulated maximum temperature (left) and apparent temperature (right) for present day and future climate.

3.4 Development of urban parameterization scheme

In addition to the above simulations the modelling group at KU Leuven developed an urban parameterization scheme (Wouters et al., 2012). This scheme has been successfully implemented in the surface module of the CCLM model. Both offline and online evaluation of this urban parameterization has been carried out, using data from Toulouse (France). The implementation of the urban parameterization scheme realistically improved the simulation of urban temperature in the Antwerp region in Belgium (Fig. 16). Further simulations are planned using the newly developed urban parameterization scheme to examine the influence of urbanization on the regional climate over Belgium.

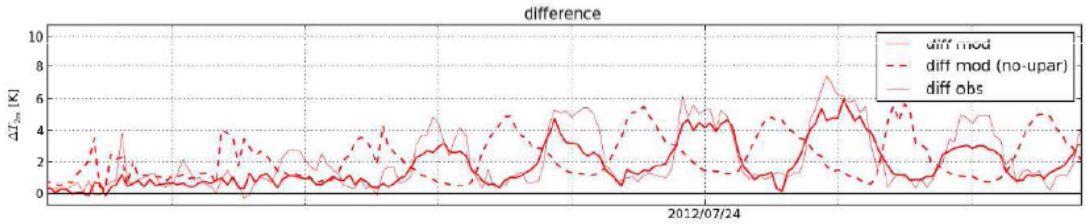


Figure 16: Temperature difference between city and rural station for the Antwerp region for a 9-day period (19-27/07/2012). Observed (solid pink), the original CCLM representation (dashed red), improved CCLM using new urban parameterization (solid red).

4 Statistical downscaling: placing the Belgian scenarios in the international context

4.1 Introduction

Albeit based on high resolution regional climate models for Belgium, the climate change impact results reported in the previous sections are based on a limited number of models. However, it is commonly agreed by the international research community that climate change impact research should be based on a large ensemble set of different climate model runs. These runs should cover a wide diversity of (i) regional climate models, (ii) global climate model in which these regional models are nested, (iii) greenhouse gas emission scenarios, and (iv) initial conditions. This is because of the high uncertainties that are present in current physical climate modelling, and in the model boundary conditions, including the future increase in greenhouse gases.

Another point of attention are the spatial and temporal scales at which the climate models operate. These scales might be too coarse for detailed impact investigations at local level. One example are applications of climate change impact analysis in hydrology. The study of the impact of climate change on local floods along a river or sewer system, or the impacts of droughts on low flows or other types of water scarcity, require good knowledge of the changes in rainfall, temperature, potential evapotranspiration, etc. at the local level (the spatial scale of one river reach or sewer pipe, or even the point scale) and at small time resolutions (5 to 10 minutes for sewer systems, 15 minutes to few hours for rivers, because these are the time scales at which these systems respond to rainfall). This difference in scales between what the climate models can offer and what the climate change impact analysis demands, can be overcome in two different ways, called dynamical or statistical downscaling.

4.2 Statistical downscaling

Dynamical downscaling involves the application of a high resolution climate model for a specific region. This is where the RMI regional climate modelling activities as presented in the previous sections focuses on. Statistical downscaling instead makes use of the climate model results at the available resolutions and applies statistical methods to transfer the climate model outputs to meteorological variables at finer scales. For instance, if regional climate model outputs are available at a spatial resolution of 25 km and at daily time scale, statistical methods can be applied to downscale these outputs to the finer scales required for hydrological impact investigation (e.g. point scale in space, hourly or 10 minutes in time).

Several statistical downscaling techniques exist. They can be broadly classified in three types: (a) transfer function based methods, (b) stochastic modelling based methods, and (c) resampling methods. The transfer function based methods (a) make use of a relation between the coarse scale climate model outputs (also called predictor variables) and the fine scale meteorological variables (called predictand variables). This function is calibrated based on historical time series data, and applied to the climate model outputs under future conditions. This can be done by regression analysis or other methods for transfer function identification and calibration. The stochastic modelling based methods (b) make use of a stochastic model to describe the fine scale meteorological variables, e.g. a weather generator. This model is again calibrated to historical time series data. By making the parameters of the model function of the coarser scale climatic data, the climate model outputs can be applied to alter the stochastic model parameters under changing climatic conditions. The third class of resampling methods (c) assess the future fine-scale meteorological variables by resampling these from the historical time series data. For each time step in the future, as simulated by the climate model, the coarse scale climate model output for that time step are used to look for an analogue time step in the past (based on similarity criteria). The fine-scale meteorological data from that analogue time step in the past is considered representative for the considered time step in the future. Extensive review on these methods can be found in Willems et al. (2012).

4.3 CCI-HYDR climate scenarios for Belgium based on statistical downscaling

For Belgium, climate change scenarios have been developed in a first version in 1998 by Gellens and Roulin (1998), and in a second version in 2008 by Ntegeka et al. (2008). The latter were obtained by the CCI-HYDR project for the Belgian Science Policy Office (BelSPO; SSD programme) (see also Baguis et al., 2009; Willems et al., 2010), and extension activities for the Institute of Nature and Forest Research (INBO; Demarée et al., 2009) and the Flemish Environment Agency (Willems et al., 2009). A recent extension was made towards fine-scale urban drainage applications (Willems and Vrac, 2011; Willems, 2013).

The CCI-HYDR climate scenarios and recent extensions were based on rather coarse scale climate model outputs, available at that moment in public data bases: the archive of global climate model simulations used for the 4^{th} Assessment Report of the IPCC, the regional climate model simulations carried out within the scope of the EU projects PRUDENCE, ENSEMBLES and ESSENCE. They had a spatial resolution of about 300 to 150 km for the global climate model simulations and 50 to 25 km for the regional climate model outputs. Because this scale was too coarse for hydrological impact investigations, statistical downscaling was applied by the CCI-HYDR project (Ntegeka et al., 2008; Ntegeka et al., 2014) and in the extension activities (Willems and Vrac, 2011; Willems, 2013). From the large ensemble set of available global and regional climate model runs, and after statistical downscaling four climate scenarios were derived, tailored for specific types of hydrological applications. They were called "winter high/wet", "summer high/wet", "mean/mild" and "low/dry" and aimed to approximately span the entire range of climate model outputs. This range reflects the total uncertainty in the climate change signal due to uncertainties in the global and regional climate modelling physics and uncertainties in the future greenhouse gases emissions. The "winter high/wet" scenario gives the strongest increase (among all the available or studied climate model outputs) in catchment runoff and river peak flows. This scenario hence was tailored for impact study on floods along the larger rivers in Belgium. For these larger rivers, floods indeed mainly occur in the winter season due to a combination of high soil saturation (high cumulative antecedent rainfall), followed by heavy rain storm(s). In the same way, the "summer high/wet" scenario is tailored for impact analysis on floods in the summer. These mainly occur only sewer systems and smaller rivers. The "mean/mild" scenario can be seen as a scenario for which about half of the available climate model output shows a stronger change, and about half a lower change. The "low/dry" scenario is applicable to drought studies, or impact analysis on low flows or water scarcity (e.g. water availability for drinking/domestic or industrial water supply, irrigation in agriculture, navigation, river valley ecology). The CCI-HYDR climate scenarios hence are applicable for impact analysis on hydrological extremes in Belgium. They were developed for the meteorological variables precipitation, temperature, potential evapotranspiration and wind speed.

Statistical downscaling methods may also include bias correction; this means correction of the climate model outputs when they systematically differ from observations during present or past climatic conditions. The assumption is then made that the same bias will be valid in the future. The CCI-HYDR scenarios also involved such bias correction, again including bias correction for rainfall extremes. Based on the bias-corrected and statistically downscaled CCI-HYDR climate scenarios, moreover a tool was developed that can be applied by hydrological modellers or water engineers to transform historical time series of rainfall, temperature, potential evapotranspiration, ... (e.g. input series in hydrological or water system models) to future conditions. This is done by means of a stochastic model algorithm that adds or removes wet and dry days from the historical time series, changes the intensities of the wet days, etc., according to each of the climate scenarios. The tool hence perturbs historical series following the climate change signals derived from the climate models, and is therefore called "perturbation tool" (Ntegeka and Willems, 2008).

4.4 New CMIP5 climate model simulations

Very recently new global climate model simulations became available: the ones used on the basis of the new 5^{th} Assessment Report of the IPCC. They are obtained by an international project called Climate Model Intercomparison Project Phase 5 (CMIP5). These new CMIP5 global climate model simulations are currently been analyzed to study the differences between the old (4^{th} Assessment Report IPCC) and the new climate model results (5^{th} Assessment report).

4.5 New climate scenario development based on high resolution Belgian climate models

The high resolution regional climate model results of the RMI and KU Leuven, as presented in the previous sections, provide unique information to improve the regional climate scenarios for Belgium. This is because they provide the first high resolution climate change information, specifically for Belgium, based on dynamical downscaling. The challenge is, however, that only a few high resolution regional climate model runs are available so far. More runs would be required to enable assessment of the uncertainty in the dynamically downscaled fine-scale climate change results. However, by positioning the global and regional climate models (in which the high resolution models are nested) in the large ensemble range of global and regional climate models available from the CMIP5 (for global climate models) and the most recent EU-project on regional climate modelling (ENSEMBLES), an uncertainty range can be assessed for the high resolution model results. This is hereafter demonstrated for the RMI results.

Comparison is first made of the regional climate model results for Belgium by RMI with the ensemble of CMIP5 results (see Table 3 in Appendix 1) for precipitation and temperature. This is done for the following regional climate model results (see also Table 4 in Appendix 2):

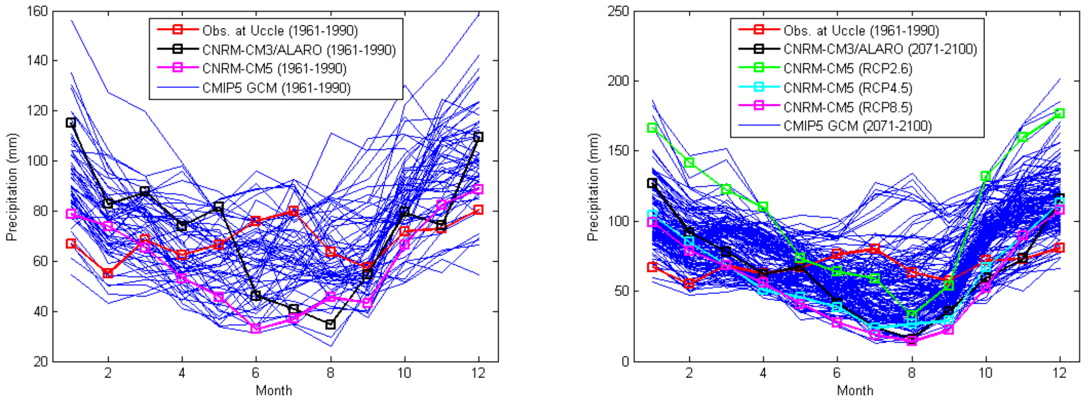
- For historical period:
  - ALARO-0 model (4 km, 10 km and 40 km spatial resolution), dynamically downscaling ERA-40 historical re-analysis data for 1961-1990 (summer periods), daily and hourly precipitation;
  - ALADIN-Climate model developed by the Centre National de Recherces Mété-orologiques (CNRM) (i.e. CNRM-RM4.5 in ENSEMBLES), dynamically downscaling ERA-40 for 1961-1990, daily precipitation.
- For future period:
  - ALARO-0 model (4 km spatial resolution), dynamically downscaling Arpège GCM results for 2071-2100, SRES scenario A1B, daily precipitation and 2-m temperature (Tmax, Tmin, Tmean) (hereafter called CNRM-CM3/ALARO-0).

This later can be extended with additional results that will become available soon, such as the more recent ERA-Interim/ALARO-0 results and the CNRM-CM5/ALARO-0 results for the new RCP scenarios 4.5 and 8.5 (2071-2100).

The comparison results are described in detail in the following paragraphs. In summary, it is concluded that the high resolution ALARO-0 model provides improved (unbiased) results for summer precipitation extremes in Belgium (see also De Troch et al., 2013).

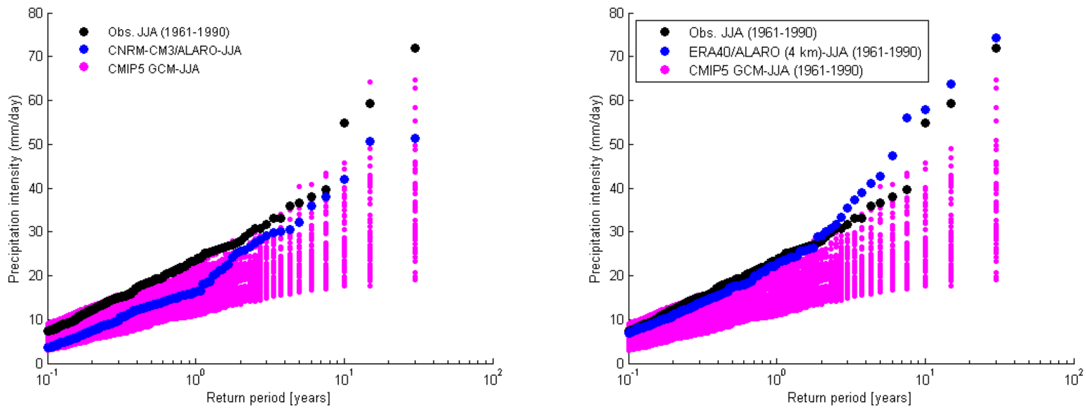
When the CNRM-CM3/ALARO-0 results are compared with the CMIP5 ensemble (Fig. 17(a) and 17(b)), it is shown that CNRM-CM3/ALARO-0 results are located on the lower side of the CMIP5 range during summer (hence providing rather dry conditions), whereas they are a bit higher than the CMIP5 ensemble mean during winter. For the daily precipitation extremes, whereas these extremes are systematically overestimated in the winter season (not shown), they perform much better in the summer season (Fig. 18(a)). As expected, the higher spatial resolution of the ALARO-0 model does provide higher accuracy for the summer precipitation extremes: the CMIP5 summer precipitation extremes show systematic underestimations for the higher return periods, whereas this underestimation is less for the CNRM-CM3/ALARO-0 results (Fig. 18(a)). Still a small underestimation of the observed precipitation extremes at Uccle is noted in Fig. 18(a). When the CNRM-CM3/ALARO-0 results are compared with the ERA-40/ALARO-0 4 km results (Fig. 18(b)), the remaining underestimations appear to be explained by underestimations in the CNRM-CM3 model rather than in the ALARO-0 model itself. The

ERA-40/ALARO-0 4 km results are indeed unbiased for most of the summer precipitation extremes with the exception of some of the highest values. The ERA-40/ALARO-0 10 km results are more unbiased even for the highest extremes. Comparison of the ERA-40/ALARO-0 results for different spatial resolutions (4, 10 and 40 km) and that of ALADIN-Climate at 25 km does show higher biases in summer precipitation extremes for the ALADIN-Climate model than the ALARO-0 model (Fig. 19(a)). Overall, ALARO-0 shows improved results for convective precipitation extremes for different spatial resolutions.



(a) (b)

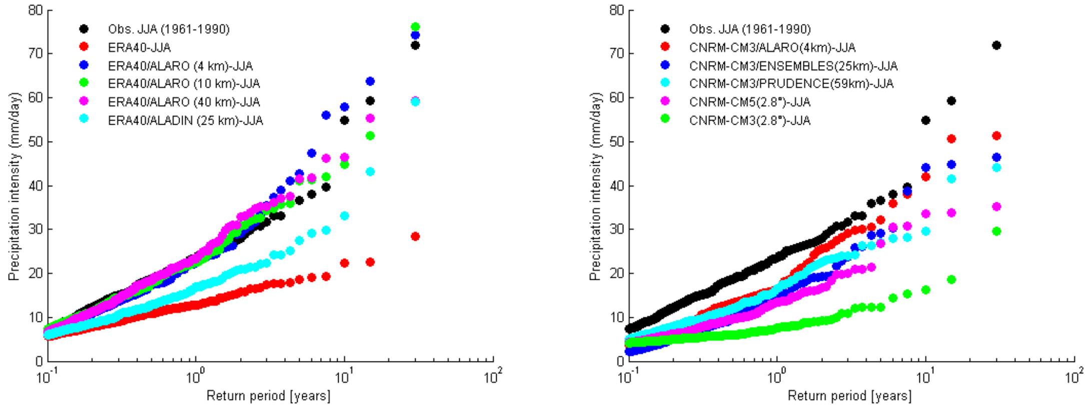
Figure 17: Comparison of the CNRM-CM3/ALARO results with the CMIP5 ensemble and Uccle observations, for monthly mean summer precipitation (left: historical climate: 1961-1990, right: future climate: 2071-2100).



(a) (b)

Figure 18: Comparison of the CNRM-CM3/ALARO 4 km results (left) and ERA40/ALARO 4km results (right) with the CMIP5 ensemble and Uccle observations, for daily precipitation quantiles (historical climate: 1961-1990, JJA).

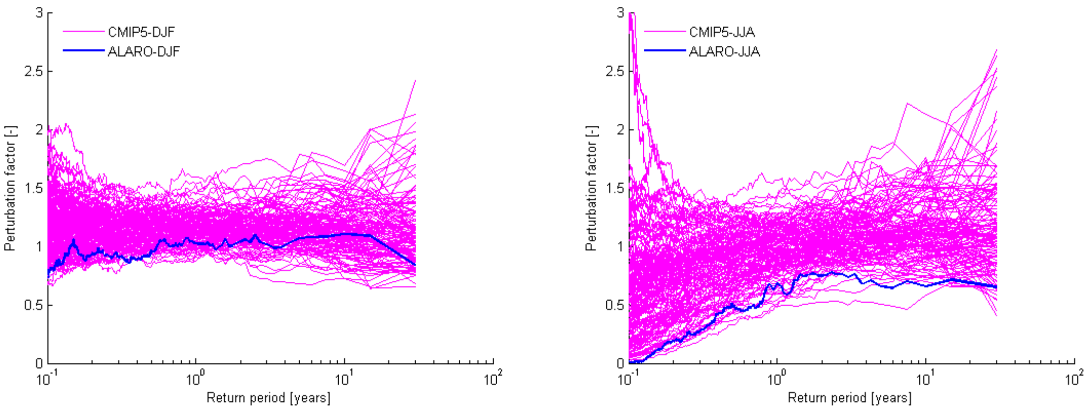
The importance of modelling summer extremes with finer resolution models is shown by comparing the CNRM GCM in the CMIP3 and CMIP5 runs with that of the CNRM-CM3 GCM that was used in PRUDENCE and ENSEMBLES projects and also the finer scale ALARO-0 model for the historical period (1961-1990) as shown in Fig. 19(b). From this figure we can see that the CNRM-CM5 model has strongly improved in its simulation when compared to CNRM-CM3 model. In terms of spatial resolution, the ALARO-0 model is better for the simulation of extremes when compared to the RCMs used in the PRUDENCE and ENSEMBLES runs and the CNRM GCMs. Rainfall extremes are, however, systematically underestimated by all the models as can be seen on Fig. 19(b). This indicates that bias correction would be necessary if the results from the models are to be used directly in impact models. The other option is to compute the change factors between the future simulations and the current climate model runs. These change factors can then be applied to the observed data transferring the climate change signals to our measurements. Question is whether the change factors obtained from the global simulations are consistent with the change factors by the higher resolution models. With this aim, the analysis is extended by computing the change factors based on the future climate runs for the period 2071-2100 versus the current climate runs for the period 1961-1990. These change factors are computed using daily quantiles of the same return period for the winter and summer season.



(a) (b)

Figure 19: Left: Comparison of the ERA40/ALARO 4, 10, 40 km and ERA40/ALADIN-Climate 25 km results with ERA40 and Uccle observations, for daily precipitation quantiles (historical climate: 1961-1990, JJA). Right: Comparison of the CNRM-CM3/ALARO 4 km results with the CMIP3 and CMIP5 CNRM runs, PRUDENCE and ENSEMBLES RCMs and Uccle observations, for daily precipitation quantiles (historical climate: 1961-1990, JJA).

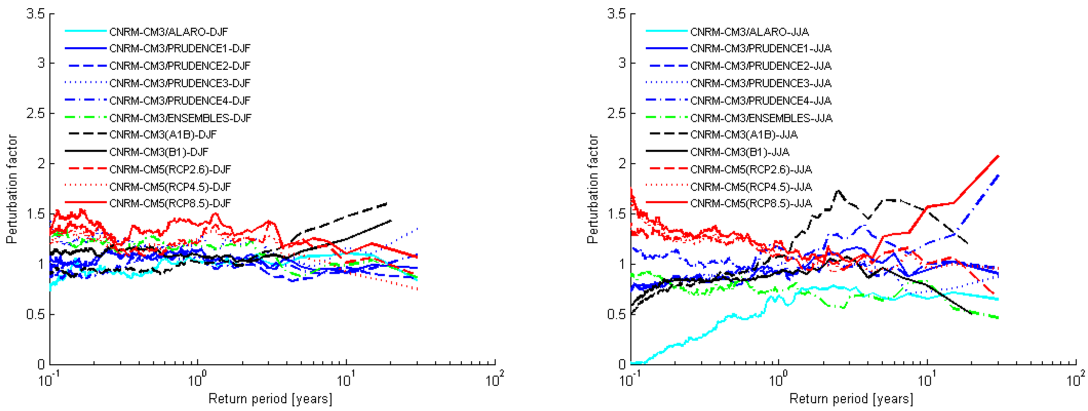
The change factors obtained using CNRM-CM3/ALARO-0 were compared with the change factors computed for CMIP5 ensemble runs. The result of CNRM-CM3/ALARO-0 is below the mean of the CMIP5 ensemble for the winter season and on the lower side of the CMIP5 ensemble for summer (Fig. 20(a) and 20(b)). The lower change factor results for summer may be consistent with the lower precipitation results for that season, as was shown in Fig. 17(a) and 17(b). The change factor range observed for the CMIP5 summer season (0.01-4.0) is wider than that of the winter season (0.6-2.4). This might have to do with the unpredictability of summer precipitation compared to the winter season.



(a) (b)

Figure 20: Comparison of CNRM-CM3/ALARO 4 km change factors for 2071-2100 vs. 1961-1990 with those of the CMIP5 ensemble for the winter season (DJF) (left) and summer season (JJA) (right).

The change factors are also compared by selecting the CNRM and CNRM-CM3 runs as shown in Fig. 21(a) and 21(b) for winter and summer season respectively. The winter season change factors obtained for CNRM-CM3 are on the lower side compared to the other runs especially for the lower extremes. The change factors obtained based on the CNRM-CM5 model scenarios project an increasing signal in the range of 20% to 40% on average. Compared to the previous model (CNRM-CM3), the change factors of CNRM-CM5 are greater. In terms of spatial resolution, it can be seen that while the coarser resolution models (red and black lines) project an increasing signal the finer resolution models (green and blue lines) project a slightly decreasing signal, but not significantly different when the differences in change factors between different models is taken into account. Therefore, the change factors that are obtained based on the finer resolution models are not necessarily stronger than the change factors for the coarser resolution models. This result is more pronounced for the summer season (Fig. 21(b)). As already discussed above, the change factors for CNRM-CM3/ALARO-0 model are much lower than the other runs that are compared. On average there is about a difference of 60% in daily summer change factors between the CNRM-CM3/ALARO-0 model and the rest of the runs. Therefore, the finer resolution ALARO-0 model shows much drier condition for the summer season in the 2071-2100 horizon. Similar to the winter season, the change factors based on CNRM-CM5 are higher than that of CNRM-CM3. Hence, when ALARO-0 results for the new RCP scenarios 4.5 and 8.5 become available the severe drier conditions might show some improvement.



(a) (b)

Figure 21: Comparison of change factor computed using the CNRM-CM3/ALARO 4 km, the CMIP3 and CMIP5 CNRM runs, PRUDENCE and ENSEMBLES RCMs for winter season (DJF) (left) and summer season (JJA) (right).

Further analysis was conducted on the historical hourly precipitation data to investigate the advantage of having finer temporal resolution. In Fig. 22, it can be seen that results of ERA-40/ALARO-0 4 km better capture the hourly maximum precipitation than the 10 km and 40 km results by ERA-40/ALARO-0 model. Comparing the daily resolution results shown in Fig. 19(a) with the hourly results obtained on Fig. 22, one can see that the dynamical downscaling of daily data provides similar result for the three spatial resolutions while for the hourly data the finer spatial resolution (4 km) has the best result. Therefore, again the importance of finer spatial resolution data is confirmed by its ability to simulate the hourly maximum precipitation similar to the observed series.

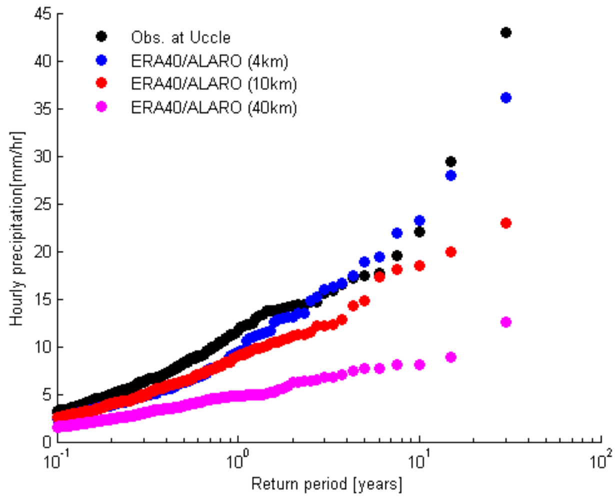


Figure 22: Comparison of hourly maximum precipitation using ERA40/ALARO 4, 10, 40 km and Uccle observations (historical climate: 1961-1990, JJA).

5 Discussion and conclusions

This report was written to propose a scientific baseline for future Belgian climate services. It presents the current status of the research activities within a limited network, with respect to the driving international evolutions, in particular the Fifth Assessment Report (AR5) of the IPCC and the ongoing CORDEX project. This report was not meant to be exhaustive and it should not be interpreted as a comprehensive overview of the climate modelling activities in Belgium. There are other research groups currently active at, for instance, the George Lemaître Centre for Earth and Climate Research (TECLIM) of the Université Catholique de Louvain, at the Département de Géography, Laboratoire de Climatologie of the university of Liège and at the Environmental Modelling Department of the Vlaamse Instelling voor Technologisch Onderzoek (VITO). The first has been working closely together with KU Leuven in the MACCBET project of BELSPO. There are also groups active at the level of the Federal Scientific Institutes such as Belgian Institute for Space Aeronomy, the Royal Belgian Institute of Natural Sciences and the Royal Observatory of Belgium.

From the results presented in Fig. 20 it can be seen that basing policy making on one single model output can lead to biased decisions. Indeed, it has been shown in Fig. 19 that ALARO performs as a state-of-the-art model when used with reanalysed observational data, but when coupled to the boundary data of its corresponding global CNRM general circulation model, the global-model bias is induced to the regional level. Said differently, the uncertainties present in the global GCM is translated to the climate generated by the regional climate model. While this effect is illustrated very clearly in this specific case of the ALARO model, it is present in all RCMs and this can only be taken into account if enough RCMs are coupled to the different members of the ensemble of models in the CMIP runs.

To develop reliable climate services we need to

- study the induced bias and apply methods to correct the model output,
- quantify the uncertainties that can be found in the CMIP and the CORDEX projects and infer them to the regional models.

The more models are available the better the spread can be quantified. Therefore it is adviced to base future climate services on data provided by a wide modelling community using scientifically validated models. At the same time it is necessary to extend the methods that were used in the CCI-HYDR project and which we used also here to devise methods for the treatment of the biases and for inferring the uncertainties present in the CMIP data and the CORDEX data to the Belgian regional level.

Appendix

1 Overview of CMIP5 global climate model ensemble

Table 3: Overview of the CMIP5 GCM results considered for the GCM ensemble (>200). With the control period: 1961-1990 and scenario period: 2071-2100

N	Model	Historical	RCP2.6	RCP4.5	RCP6.0	RCP8.5	Total
1	ACCESS 1.0	1	X	1	X	1	3
2	ACCESS 1.3	1	X	1	X	1	3
3	BCC-CSM1.1	3	1	1	1	1	7
4	BCC-CSM1.1(m)	1	1	1	1	1	5
5	BNU-ESM	1	1	1	X	1	4
6	CCSM4	1	1	1	3	1	7
7	CAM5	1	1	2	3	3	10
8	CANESM2	5	5	5	X	5	20
9	CMCC-CM	1	X	1	X	1	3
10	CMCC-CMS	1	X	1	X	1	3
11	CMCC-CESM	1	X	X	X	1	2
12	CNRM-CM5	1	1	1	X	1	4
13	CSIRO-MK3.6.0	10	10	10	10	10	50
14	EC-EARTH	1	X	1	X	3	5
15	FGOALS-G2	1	1	1	X	1	4
16	GFDL-CM3	2	1	3	1	1	8
17	GFDL-ESM2G	1	1	1	1	1	5
18	GFDL-ESM2M	1	X	1	1	1	4
19	GISS-E2-H	2	X	X	X	X	2
20	GISS-E2-R	3	X	2	X	X	5
21	HADGEM2-AO	1	1	1	1	1	5
22	HADGEM2-CC	3	X	1	X	1	5
23	HADGEM2-ES	1	1	2	1	2	7
24	INM-CM4	1	X	1	X	1	3
25	IPSL-CM5A-LR	4	1	4	1	4	14
26	IPSL-CM5A-MR	1	1	1	1	1	5
27	IPSL-CM5B-LR	1	X	1	X	1	3
28	MIROC-ESM	1	1	1	1	1	5
29	MIROC-ESM-CHEM	1	1	1	1	1	5
30	MIROC5	3	2	1	1	3	10
31	MPI-ESM-LR	1	1	1	X	1	4
32	MPI-ESM-MR	1	1	1	X	1	4
33	MRI-CGCM3	1	1	1	1	1	5
34	NORESM1-M	3	1	1	1	1	7

2 Overview of model runs considered in the statistical downscaling analysis

Table 4: Overview of model runs considered in the statistical downscaling analysis

		GCM	Reanalysis	RCM	Scenario	Spatial resolution	Temporal resolution	Period historical	Period future	Rainfall	Tmax	Tmin	Tmean	Seasons	Area	Database
Runs received from RMI	1	Arpege		ALARO-0	A1B	4 km	daily	1961-1990	2071-2100	X	X	X	X	All	Belgium & Uccle	
	2	Arpege					daily	1961-1990	2071-2100		X	X	X	Summer	Uccle	
	3		ERA-40	ALARO-0		4, 10, 40 km	daily	1961-1990		X				Summer	Belgium & Uccle	
	4		ERA-40	ALARO-0		4, 10, 40 km	hourly	1961-1990		X				Summer	Uccle	
	5		ERA-40				daily	1961-1990		X				Summer	Belgium & Uccle	
	6		ERA-40	ALADIN-Climate		25 km	daily	1961-1990		X				Summer	Belgium & Uccle	ENSEMBLES
	7		ERA-Interim	ALARO-0+SURFEX		4 km	daily	1980-2010		X				All	Belgium & Uccle	
	8		ERA-Interim	ALARO-0+SURFEX		4 km	hourly	1980-2010		X				Summer	Uccle	
Runs from other databases	1	CNRM-DC9		ARPEGE stretched	A2	59 km	daily	1961-1990	2071-2100	X				All	Uccle	PRUDENCE
	2	CNRM-DE5		ARPEGE stretched	A2	59 km	daily	1961-1990	2071-2100	X				All	Uccle	PRUDENCE
	3	CNRM-DE6		ARPEGE stretched	A2	59 km	daily	1961-1990	2071-2100	X				All	Uccle	PRUDENCE
	4	CNRM-DE7		ARPEGE stretched	A2	59 km	daily	1961-1990	2071-2100	X				All	Uccle	PRUDENCE
	5	ARPEGE		HIRHAM5	A1B	25 km	daily	1961-1990	2071-2100	X				All	Uccle	ENSEMBLES
	6	CNRM-CM3			A1B	2.8° (i.e. 300 km)	daily	1961-1990	2081-2100	X	X	X	X	All	Uccle	CMIP3
	7	CNRM-CM3			B1	2.8° (i.e. 300 km)	daily	1961-1990	2081-2100	X	X	X	X	All	Uccle	CMIP3
	8	CNRM-CM5			RCP2.6	1.4° (i.e. 150 km)	daily	1961-1990	2071-2100	X	X	X	X	All	Uccle	CMIP5
	9	CNRM-CM5			RCP4.5	1.4° (i.e. 150 km)	daily	1961-1990	2071-2100	X	X	X	X	All	Uccle	CMIP5
	10	CNRM-CM5			RCP8.5	1.4° (i.e. 150 km)	daily	1961-1990	2071-2100	X	X	X	X	All	Uccle	CMIP5

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References

ALADIN international team, 1997: The ALADIN project: Mesoscale modelling seen as a basic tool for weather forecasting and atmospheric research. *WMO Bull.*, **46**, 317–324.

Baede, A., 2007: Annex I: Glossary. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press, 941–954.

Baguis, P., E. Roulin, P. Willems, and V. Ntegeka, 2009: Climate change scenarios for precipitation and potential evapotranspiration over central Belgium. *Theoretical and Applied Climatology*, **99**, 273–286.

Böhm, U., M. Kücken, W. Ahrens, A. Block, D. Hauffe, K. Keuler, B. Rockel, and A. Will, 2006: The climate version of LM: Brief description and long-term applications. *COSMO Newsletter*, **6**, 225–235.

Bubnová, R., G. Hello, P. Bénard, and J.-F. Geleyn, 1995: Integration of the fully elastic equations cast in the hydrostatic pressure terrain-following coordinate in the framework of the ARPEGE/Aladin NWP system. *Mon. Wea. Rev.*, **123**, 515–535.

De Troch, R., R. Hamdi, H. Van de Vyver, J.-F. Geleyn, and P. Termonia, 2013: Multiscale performance of the ALARO-0 model for simulating extreme summer precipitation climatology in Belgium. *J. Climate*, **26**, 8895–8915, doi:10.1175/JCLI-D-12-00844.1.

Demarée, G., et al., 2009: Klimaatscenario's voor Vlaanderen. Rapport voor het Instituut voor Natuur- en Bosonderzoek (INBO), Koninklijk Meteorologisch Instituut van België, Koninklijk Nederlands Meteorologisch Instituut (KNMI) and KU Leuven-afdeling Hydraulica January 2009.

Gellens, D. and E. Roulin, 1998: Streamflow response of Belgian catchments to IPCC climate change scenarios. *Journal of Hydrology*, **210**, 242–258, doi:10.1016/S0022-1694(98)00192-9.

Gerard, L., J.-M. Piriou, R. Brožková, J.-F. Geleyn, and D. Banciu, 2009: Cloud and precipitation parameterization in a meso-gamma-scale operational weather prediction model. *Mon. Wea. Rev.*, **137**, 3960–3977, doi:10.1175/2009MWR2750.1.

Hamdi, R., H. Van de Vyver, R. De Troch, and P. Termonia, 2014: Assessment of three dynamical urban climate downscaling methods: BrusselsâĂŹs future urban heat island under an a1b emission scenario. *Int. J. Climatol.*, **34**, 978–999.

Hamdi, R., H. Van de Vyver, and P. Termonia, 2012: New cloud and microphysics parameterisation for use in high-resolution dynamical downscaling: application for summer extreme temperature over Belgium. *Int. J. Climatol.*, **32**, 2051–2065, doi:10.1002/joc.2409.

Haylock, M. R., N. Hofstra, A. M. G. Klein Tank, E. J. Klok, P. D. Jones, and M. New, 2008: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950-2006. *J. Geophys. Res.*, **113**, 12, doi:10.1029/2008JD010201.

Hazeleger, W., et al., 2010: EC-Earth: A seamless earth-system prediction approach in action. *Bull. Amer. Meteor. Soc.*, **91**, 1357–1363, doi:10.1175/2010BAMS2877.1.

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. B. Mitchell, 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Amer. Meteor. Soc.*, **88**, 1383–1394, doi:10.1175/BAMS-88-9-1383.

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston, 2012: An overview of the global historical climatology network-daily database. *J. Atmos. Oceanic Technol.*, **29**, 897–910, doi:10.1175/JTECH-D-11-00103.1.

Ntegeka, V., P. Baguis, O. Boukhris, P. Willems, and E. Roulin, 2008: Climate change impact on hydrological extremes along rivers and urban drainage systems. II. Study of rainfall and eto climate change scenarios. Interim report for Belgian Science Policy Office, KU Leuven - Hydraulics division and Royal Meteorological Institute of Belgium May 2008, 112 pp. Http://www.kuleuven.be/hydr/CCI-HYDR.htm.

Ntegeka, V., P. Baguis, E. Roulin, and P. Willems, 2014: Developing tailored climate change scenarios for hydrological impact assessments. *Journal of Hydrology*, **508C**, 307–321, doi:10.1016/j.jhydrol.2013.11.001.

Ntegeka, V. and P. Willems, 2008: CCI-HYDR Perturbation Tool: a climate change tool for generating perturbed time series for the Belgian climate. Manual, KU Leuven âĂŞ Hydraulics division and Royal Meteorological Institute of Belgium December 2008, 7 pp. Http://www.kuleuven.be/hydr/CCI-HYDR.htm.

Radu, R., M. Déqué, and S. Somot, 2008: Spectral nudging in a spectral regional climate model. *Tellus A*, **60**, 898–910, doi:10.1111/j.1600-0870.2008.00341.x.

Skalák, P., P. Stepánek, and A. Farda, 2008: Validation of ALADIN-Climate/CZ for present climate (1961-1990) over the Czech Republic. *Quarterly Journal of the Hungarian Meteorological Service*, **112**, 191–201.

Steppeler, J., G. Doms, U. Schättler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric, 2003: Mesogamma scale forecasts using the nonhydrostatic model LM. *Meteor. Atmos. Phys.*, **82**, 75–96.

Uppala, S. M., et al., 2005: The ERA-40 re-analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012, doi:10.1256/qj.04.176.

Willems, P., 2013: Revision of urban drainage design rules after assessment of climate change impacts on precipitation extremes at Uccle, Belgium. *Journal of Hydrology*, **496**, 166–177, doi: 10.1016/j.jhydrol.2013.05.037.

Willems, P., P. Deckers, P. De Maeyer, R. De Sutter, W. Vanneuville, J. Brouwers, and B. Peeters, 2009: Klimaatverandering en waterhuishouding. Wetenschappelijk rapport, MIRA 2009 and NARA 2009, Vlaamse Milieumaatschappij en Instituut voor Natuur- en Bosonderzoek. Www.milieurapport.be en www.nara.be.

Willems, P., V. Ntegeka, and P. B. E. Roulin, 2010: Climate change impact on hydrological extremes along rivers and urban drainage systems. Final report for Belgian Science Policy Office, KU Leuven - Hydraulics Section and Royal Meteorological Institute of Belgium December 2010, 110 pp. Http://www.kuleuven.be/hydr/CCI-HYDR.htm.

Willems, P., J. Olsson, K. Arnbjerg-Nielsen, S. Beecham, A. Pathirana, I. B. Gregersen, H. Madsen, and V.-T.-V. Nguyen, 2012: *Impacts of climate change on rainfall extremes and urban drainage*. IWA Publishing, 252 pp.

Willems, P. and M. Vrac, 2011: Statistical precipitation downscaling for small-scale hydrological impact investigations of climate change. *Journal of Hydrology*, **402**, 193–205, doi:10.1016/j.jhydrol.2011.02.030.

Wouters, H., K. De Ridder, and N. P. M. van Lipzig, 2012: Comprehensive parametrization of surface-layer transfer coeffcients for use in atmospheric models. *Boundary-layer meteorology*, **145**, 539–550.

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