VLAAMSE MILIEUMAATSCHAPPIJ

KU LEUVEN

Actualisatie en verfijning klimaatscenario's tot 2100 voor Vlaanderen

Appendix 1: Nieuwe modelprojecties voor Ukkel op basis van Europese en Belgische fijnmazige klimaatmodellen

Studie uitgevoerd in opdracht van
MIRA, Milieurapport Vlaanderen

Onderzoeksrapport

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Documentbeschrijving

Titel
Actualisatie en verfijning klimaatscenario's tot 2100 voor Vlaanderen - Appendix 1: Nieuwe modelprojecties voor Ukkel op basis van Europese en Belgische fijnmazige klimaatmodellen.

Dit rapport verschijnt in de reeks MIRA Ondersteunend Onderzoek van de Vlaamse Milieumaatschappij. Deze reeks bevat resultaten van onderzoek gericht op de wetenschappelijke onderbouwing van het Milieurapport Vlaanderen.

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Samenwerking
De hoge-resolutie klimaatmodelresultaten voor België werden ter beschikking gesteld door:
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Inhoud
Dit is de 1e technische Appendix (Engelstalig) bij het MIRA rapport 'Actualisatie en verfijning klimaatscenario's tot 2100 voor Vlaanderen'. Ze rapporteert de resultaten van de CORDEX-modellen en de MACCBET modellen, die werden geanalyseerd voor Ukkel. Deze analyse was noodzakelijk om de hoge-resolutie klimaatrun te kunnen interpreteren binnen het CORDEX ensemble. Vanwege de hoge computerkosten die de hoge-resolutie runs met zich meebrengen, werd binnen het MACCBET project voor België slechts een aantal CMIP5 modellen (EC-Earth) dynamisch neergeschaald.

Wijze van refereren
Beullens J. & van Lipzig N.P.M. (2015), Actualisatie en verfijning klimaatscenario's tot 2100 voor Vlaanderen - Appendix 1: Nieuwe modelprojecties voor Ukkel op basis van Europese en Belgische fijnmazige klimaatmodellen. Studie uitgevoerd in opdracht van de Vlaamse Milieumaatschappij, MIRA, MIRA/2015/02, KU Leuven. Raadpleegbaar op www.milieurapport.be.

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1. Introduction

This appendix reports the results of the statistical analyzes done for the regional climate models of CORDEX, MACCBET and ALARO. For CORDEX eleven RCM's (=Regional Climate Models) were used, for both RCP4.5 and RCP8.5 scenario, with a spatial resolution of 50 km. For MACCBET four runs were available, one for the present day, two for the RCP4.5 scenario (2030 and 2064) and one for the RCP8.5 scenario (2064), with a spatial resolution of 3 km. The MACCBET model is therefore a high resolution model. Another high resolution model is the ALARO model from the RMI (=Royal Meteorological Institute of Belgium) with a spatial resolution of 4 km.

First a description of the different models is given. In the second part of this appendix model projections were made for the CORDEX runs for the grid cell of Uccle. This was done for the yearly temperature, summer- and winter precipitation. What the advantage of a high resolution model is, compared to a model with a lower resolution will be explained in this appendix and the high resolution models will be located in the ensemble of the CORDEX runs. This was done by the use of the climate sensitivity. This is the mean increase or decrease of a variable (ex. Temperature) over a period of 100 years. The climate sensitivity was at every turn modelled for the grid cell of Uccle. For the Belgian model projections, one model run was used to look at the extremes, the FUT2064_RCP8.5 run. This scenario run is lying for temperature and precipitation in the middle of the CORDEX ensemble. It is important to know that these results are only results from one member of the ensemble, so be careful with the interpretation of these data.

2. Regional climate models

2.1. CORDEX

The need for finer representations of the spatial variability has been the main driving factor for constantly increasing the resolution of Regional Climate Models (RCMs). The continuous growth of computing resources has made such an increase of resolution possible. In the latest internationally coordinated projects, the typical size of RCM grid-mesh ranged from 50 km to 25 km (PRUDENCE and ENSEMBLES respectively (Christensen and Christensen, 2007; van der Linden and Mitchell (eds.), 2008). More recently the EURO-CORDEX program started climate integrations over Europe characterised by a 12 km grid mesh (Gobiet and Jacob, 2012). This resolution increase was found to improve the representation of the precipitation probability function and more specifically the representation of small-scale convective precipitation due to a refinement of surface characteristics (Boberg et al., 2009). However, increasing the resolution does not necessarily correct all deficiencies observed in RCMs. For example the diurnal cycle of precipitation is still characterised by a maximum occurring too early in the afternoon when increasing RCM resolution from 50 km to 12 km (Walther et al., 2013; Clark et al., 2007). This is mainly due to deficiencies in the parametrisation of deep convection which does not correctly estimate the atmospheric instabilities leading to convective activity.

In this VMM study, an analysis was performed for 11 CORDEX climate models using a resolution of 50 km and 5 models using a resolution of 12 km (Table 1) for both emission scenarios (RCP4.5 and RCP8.5). The data for this models is available for the period 2006-2100.

Table 1: Regional climate models CORDEX (50 km and 12 km resolution)

model	Δx=50 km	Δx=12 km
RACMO22E	v	v
CCLM4-8-17	v	v
RCA4_CCCma	v	x
RCA4_CNRM	v	v
RCA4_ICHEC	v	v
RCA4_IPSL	v	x
RCA4_MIROC	v	x
RCA4_MOHC	v	v
RCA4_MPI	v	x
RCA4_NCC	v	x
RCA4_NOAA	v	x

2.2. MACCBET

A few recent studies have shown the multiple benefits of performing regional climate model simulations at a scale of three kilometre or lower (Kendon et al., 2012; Prein et al., 2013; Ban et al., 2014). Using three different RCMs, Prein et al. (2013) show that both the representation of the precipitation diurnal cycle and hourly distribution are significantly improved in summer months in these kilometre-scale RCMs. On daily time-scales, the added value mainly lies in the representation of high precipitation quantiles (>90 percentile) (Ban et al., 2014). On hourly and daily time-scales the representation of the structure of precipitation patterns is also improved (Prein et al., 2013; Brisson et al., 2014). Most improvements described here are found for the summer period due to highly convective activity during this season. On monthly time-scales, the added value of kilometre scale RCMs is expected to be smaller.

The MACCBET or Modelling Atmospheric Composition and Climate for the Belgian Territory program provides projections of the future climate for Belgium at this very high resolution of 3 km. This resolution gives a better representation of explicit convection, which is parameterised in the lower resolution models. All simulations of this study were performed using the Consortium for Small-scale Modelling in climate mode (COSMO-CLM) model. The COSMO-CLM model is a non-hydrostatic limited area climate model, based on the COSMO model which is also used for operational weather forcasting (Steppeler et al., 2003).

A three-step strategy shown in Figure xx. is used in this study. The driving data is, therefore, nested in a 100x100 grid points domain with a 25 km grid mesh size. The resulting three hourly outputs are nested in a 7 km grid domain. Finally, the hourly outputs of the latter nest, characterized by 150x150 grid points, are used as input for the 3 km simulation on a 192x175 grid points domain. Note that the driving data for the 25 km domain is either the Re-analyses of the European Center for Medium-range Weather forecasts (ERA-Interim) or the data from the Global Climate Model (GCM) EC-Earth.

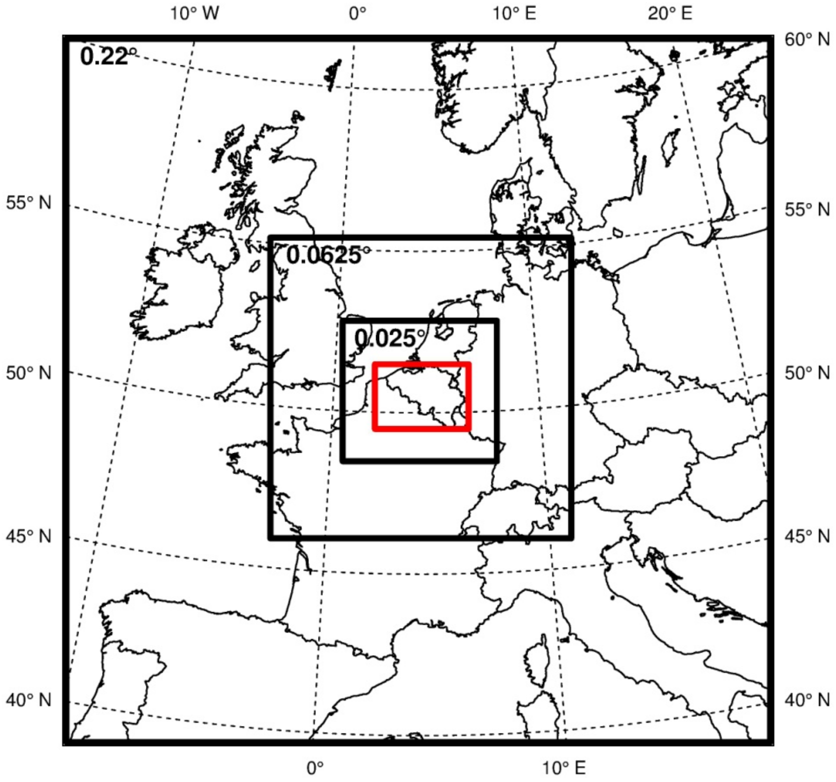


Figure 1: Map of the three MACCBET simulation nests (black) and the evaluation domain (red)

Data for this high resolution model is available for 4 periods. Period 1 (PRES_EC) is the control period from 2001 till 2010. Period 2 (FUT2030_RCP4.5) is the period going from 2026 till 2035 and is based on a RCP4.5 scenario. Period 3 (FUT2064_RCP4.5) is going from 2060 till 2069 and is also based on a RCP4.5 scenario and period 4 (FUT2064_RCP8.5) is also going from 2060 till 2069, but is based on a RCP8.5 scenario. Table 2 shows the different Belgian climate model runs, with the period, the lateral boundary, the scenario and the acronym.

Table 2: Belgian climate scenarios (MACCBET$_{(1)}$ and ALARO$_{(2)}$)

period	lateral boundary	scenario	acronym
1961-1990$_{(2)}$	ERA-40	/	HIST_ERA
2001-2010$_{(1)}$	ERA-Interim	/	PRES_ERA
2001-2010$_{(1)}$	EC-Earth	/	PRES_EC
2026-2035$_{(1)}$	EC-Earth	RCP4.5	FUT2030_RCP4.5
2060-2069$_{(1)}$	EC-Earth	RCP4.5	FUT2064_RCP4.5
2060-2069$_{(1)}$	EC-Earth	RCP8.5	FUT2064_RCP8.5
2071-2100$_{(2)}$	Arpège	SRES A1B	FUT2085_A1B

The 10-year climate scenario simulations were a major challenge due to the huge computation costs and data storage requirements; the full set of simulations took 600 000 Central Processing Unit (CPU) hours, using over 128 processors of the High Performance Computing (HPC) facility of KU Leuven. However thanks to these efforts, a database of 125 Terabytes (similar to >100,000 CD's) containing the results of the climate projections, are available for analysis. Key variables like the precipitation amount, atmosphere water divergence, cape of mean surface layer parcel, drag coefficient of momentum, vertically integrated cloud ice, cloud water, graupel, snow and water vapour content are available at an impressive time interval of 15 minutes.

2.3. ALARO (Royal Meteorological Institute)

ALARO is a numeric weather model operationally used by the Royal Meteorological Institute (RMI) of Belgium for the daily weather predictions as well as for climate studies. The ALARO model is a new version of the ALADIN model with new physical parameterizations that are centered around an improved convection and cloud scheme (Gerard et al., 2009).

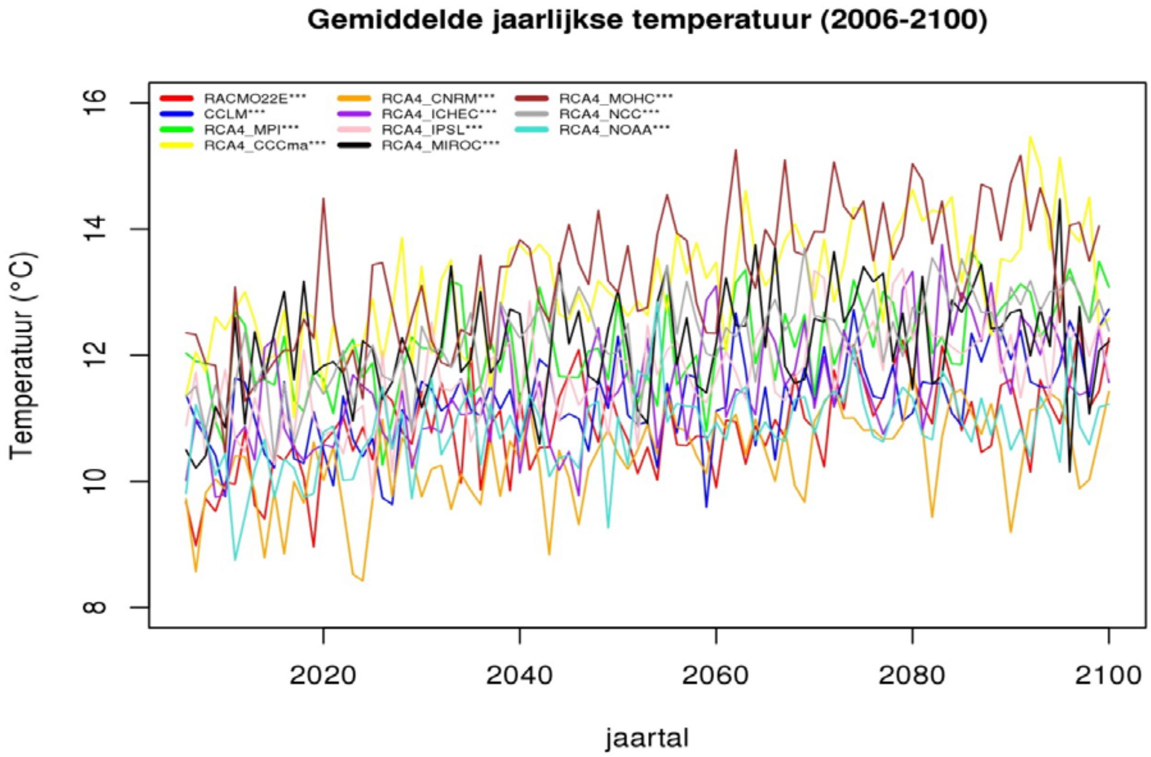
The difference with the MACCBET runs is that the ALARO run is not continuous. The procedure is to interpolate the original ERA-40 or GCM Arpège files to a 40 km resolution domain that encompasses most of western Europe. These 6-h files serve as initial and boundary conditions for a 48-h ALARO run at 40 km resolution, which is started at 0000 UTC every day. The (3 h) output from this first run serves as input for the high-resolution 4 km run on a 181x181 grid points domain centered on Belgium. However, to exclude spinup problems, the first 12 h are not taken into account. So we have 36 h of data left for the 4 km run (which thus start at 1200 UTC). Finally, we again dismiss the first 12 h of the run, to arrive at 24 h of output at 4 km resolution, and then integrate/reinitialize over each subsequent 24-h period.

3. CORDEX model projections for Uccle

The results of all the runs were statistically analysed for yearly, seasonally and monthly mean values for precipitation, temperature, evapotranspiration and wind speed. Besides the mean values, the extreme values were also analysed (number of days with a maximum temperature above 25 °C and 30 °C, number of days with a maximum and minimum temperature under 0 °C, number of dry days and wet days, the number of extreme drought events and the number of extreme rain days).

3.1. Yearly temperature

For both RCP scenarios the yearly temperature for all the CORDEX runs will increase drastically by the end of the century. The increase in temperature is higher for the RCP8.5 scenario (around 3.5 °C) than for the RCP4.5 scenario (around 1.5 °C). Table 3 gives the exact value of the expected increase for all the CORDEX runs, for the MACCBET runs and for the ALARO run. Three methods are shown in the table. The first method is a linear regression. The second method is the difference between period 2 en period 1 and rescaled for 100 years ([FUT2030_RCP4.5 – PRES_EC]/25*100). The third method is the difference between period 3 or 4 and period 1 and rescaled for 100 years ([FUT2064 – PRES_EC]/59*100 and for Uccle [FUT2085_A1B-HIST_ERA]/110*100). There can be concluded that the temperature will increase by the end of the century. How much it will increase, will depend on which RCP scenario we will follow. All the CORDEX runs show a significant increase on the 99 % significance level.



* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

Figure 2: Mean yearly temperature 2006-2100 (RCP4.5)

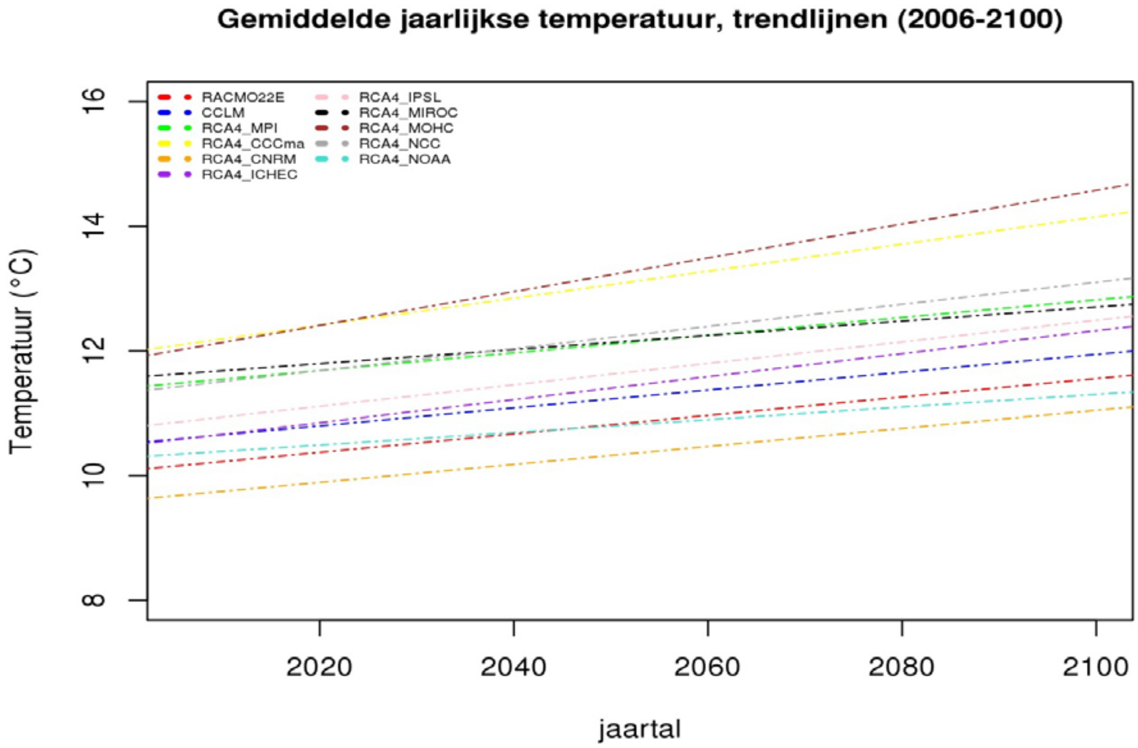
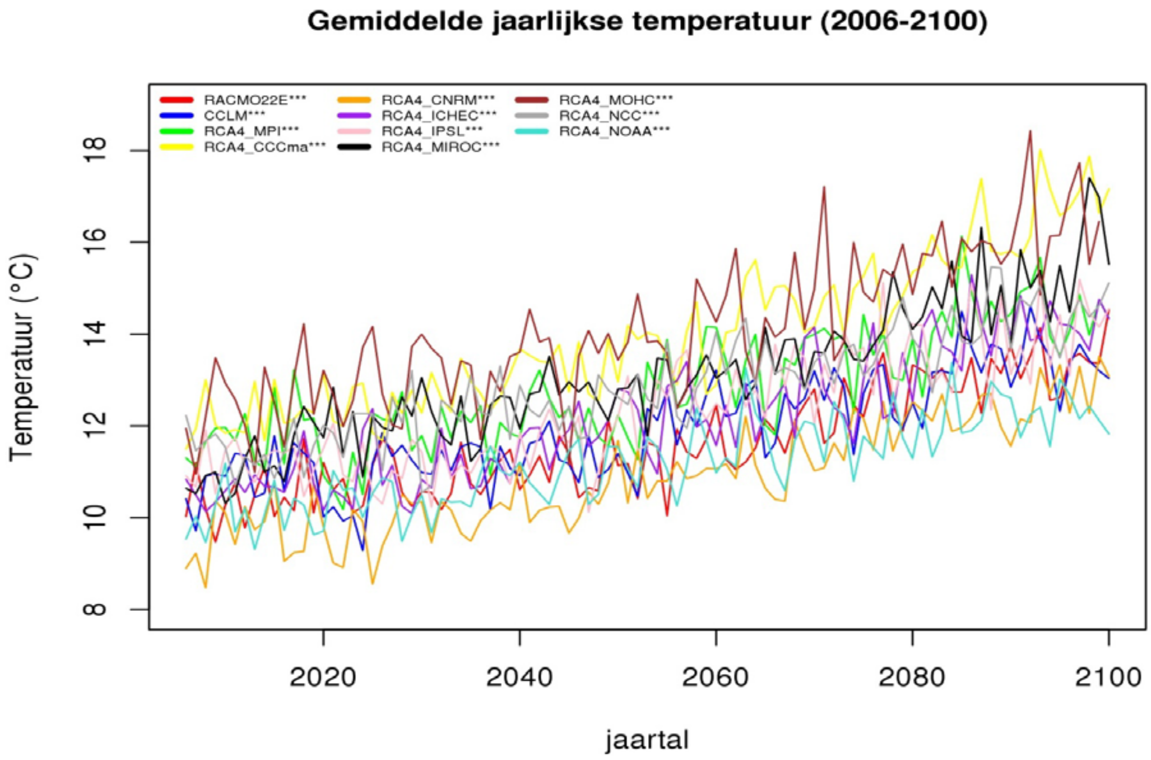


Figure 3: Mean yearly temperature 2006-2100 (RCP4.5), trend lines

Table 3: Temperature increase (°C) per 100 years for every model (RCP4.5)

model	ΔT/100 years (°C) (method 1)	ΔT/100 years (°C) (method 2)	ΔT/100 years (°C) (method 3)
CCLM***	1.43	1.74	1.23
RACMO22E***	1.61	3.71	2.24
RCA4 CCCma***	2.17	1.97	2.21
RCA4 CNRM***	1.45	1.53	1.58
RCA4 ICHEC***	1.85	1.78	1.95
RCA4 IPSL***	1.73	2.65	1.94
RCA4 MIROC***	1.13	3.97	2.02
RCA4 MOHC***	2.71	3.51	3.66
RCA4 MPI***	1.41	1.52	0.96
RCA4 NCC***	1.77	2.86	2.13
RCA4 NOAA***	1.02	3.27	1.81
MACCBET	/	4.32	1.14
ALARO	/	/	2.58

* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant



* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

Figure 4: Mean yearly temperature 2006-2100 (RCP8.5)

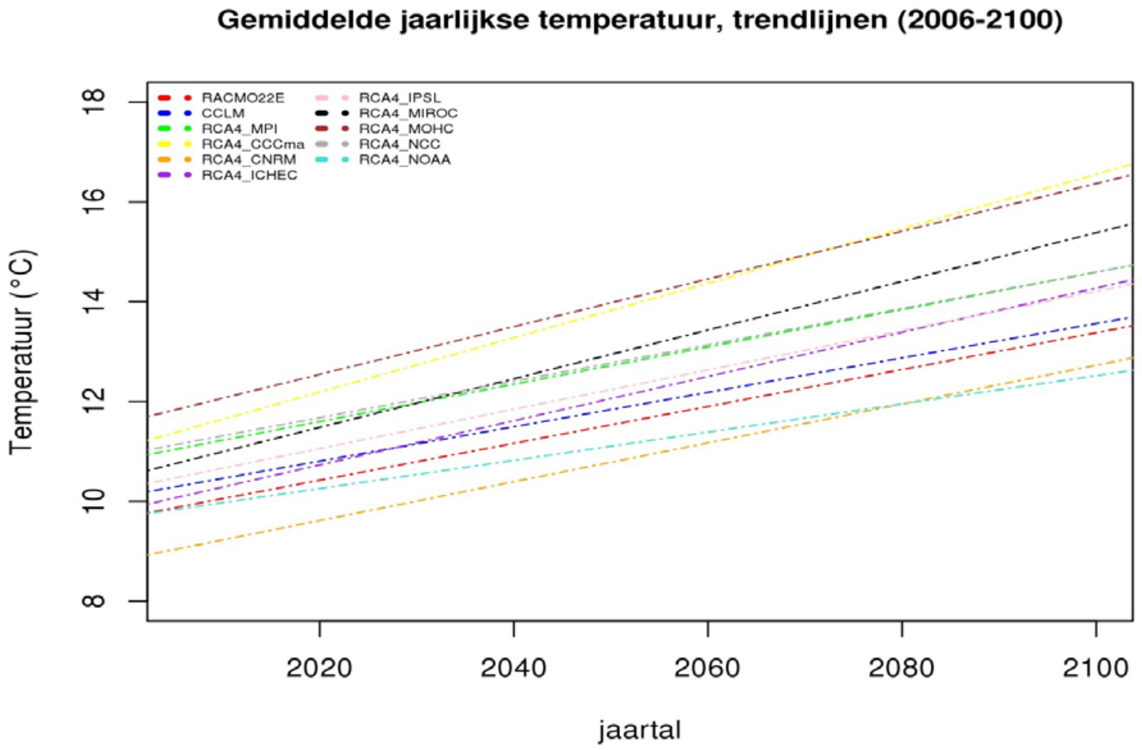


Figure 5: Mean yearly temperature 2006-2100 (RCP8.5), trend lines

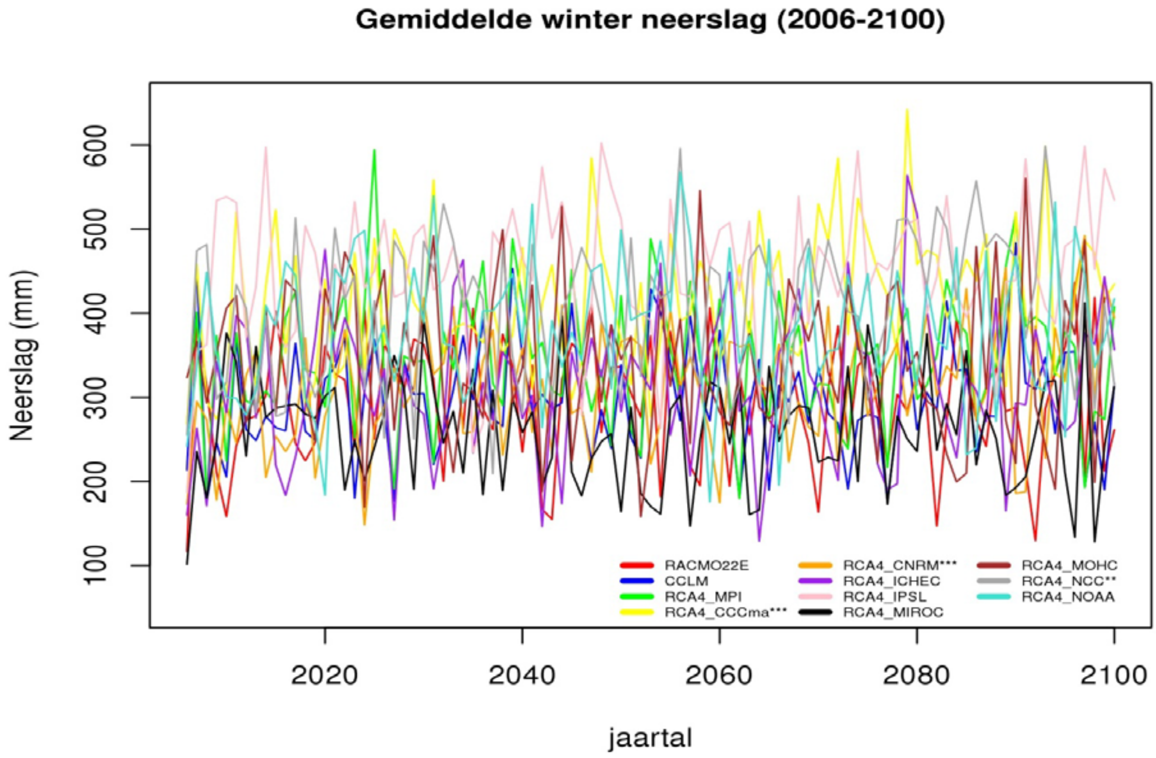
Table 4: Temperature increase (°C) per 100 years for every model (RCP8.5)

model	ΔT/100 years (°C) (method 1)	ΔT/100 years (°C) (method 2)	ΔT/100 years (°C) (method 3)
CCLM***	3.45	1.90	2.83
RACMO22E***	3.70	2.00	3.12
RCA4 CCCma***	5.46	2.90	4.18
RCA4 CNRM***	3.89	1.50	2.58
RCA4 ICHEC***	4.43	1.98	3.49
RCA4 IPSL***	3.94	3.64	3.36
RCA4 MIROC***	4.88	4.65	4.63
RCA4 MOHC***	4.78	3.31	4.21
RCA4 MPI***	3.74	3.28	2.67
RCA4 NCC***	3.65	3.65	3.30
RCA4 NOAA***	2.83	2.44	2.61
MACCBET	/	/	2.24

* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

3.2. Winter precipitation

For the winter precipitation the trends are not as clear as those for the yearly temperature. Only three of the eleven models show significant change for the RCP4.5 scenario. The RCP8.5 scenario has eight runs with a significant change. These runs that are show an clearly increase in winter precipitation. By the end of the century the amount of precipitation in the winter will increase in Belgium.



* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

Figure 6: Mean winter precipitation 2006-2100 (RCP4.5)

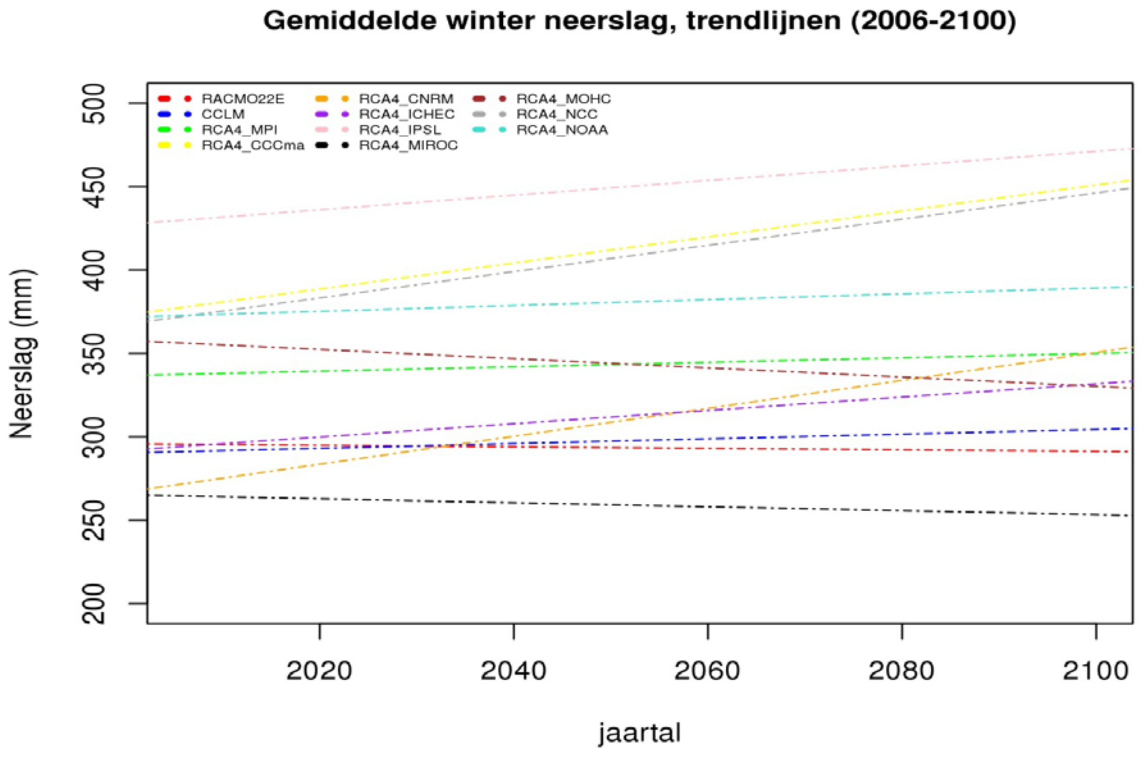
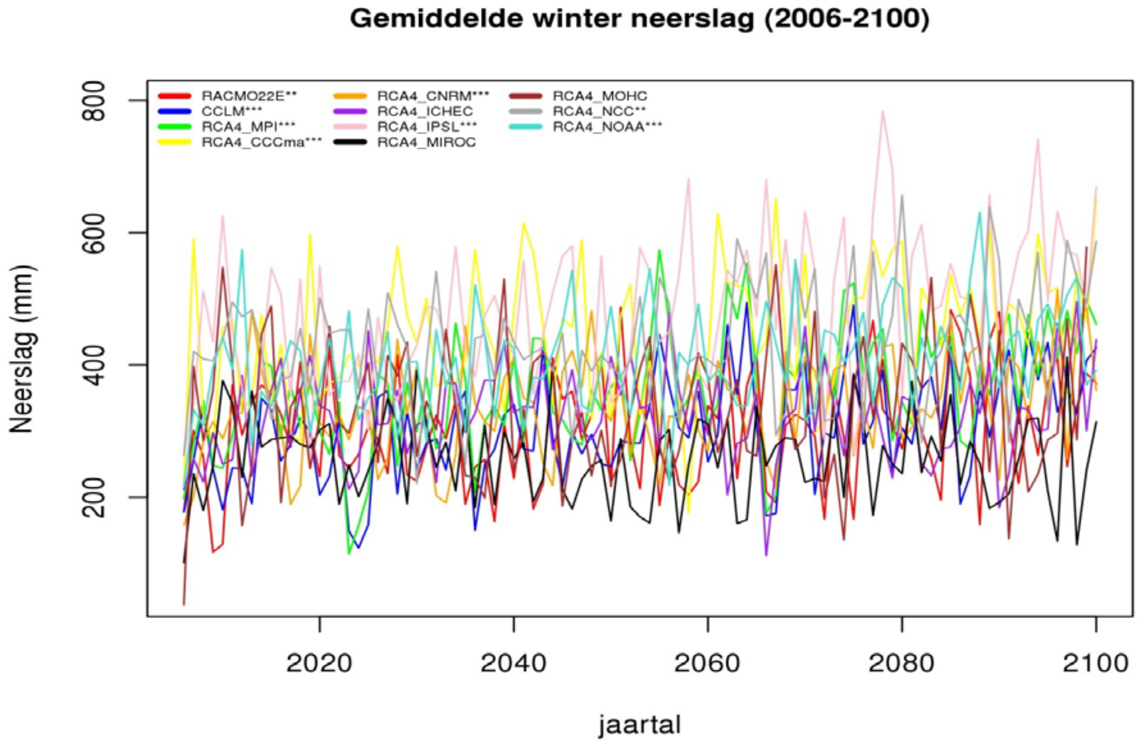


Figure 7: Mean winter precipitation 2006-2100 (RCP4.5), trend lines

Table 5: Mean winter precipitation change (mm) per 100 years for every model (RCP4.5)

model	**ΔPw/100 years (mm) (method 1)**	**ΔPw/100 years (mm) (method 2)**	**ΔPw/100 years (mm) (method 3)**
CCLM	14.14	148.67	-2.56
RACMO22E	-6.21	177.78	5.59
RCA4 CCCma***	77.95	102.37	124.96
RCA4 CNRM***	83.77	246	71.87
RCA4 ICHEC	39.9	99.7	69.9
RCA4 IPSL	43.84	-18.04	45.16
RCA4 MIROC	-11.94	-6.54	2.5
RCA4 MOHC	-27.59	5.87	30.93
RCA4 MPI	13.34	253.17	25.71
RCA4 NCC**	78.74	170.01	96.95
RCA4 NOAA	17.49	219.92	72.45
MACCBET	/	-0.44	-3.68
ALARO	/	/	3.94

* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant



* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

Figure 8: Mean winter precipitation 2006-2100 (RCP8.5)

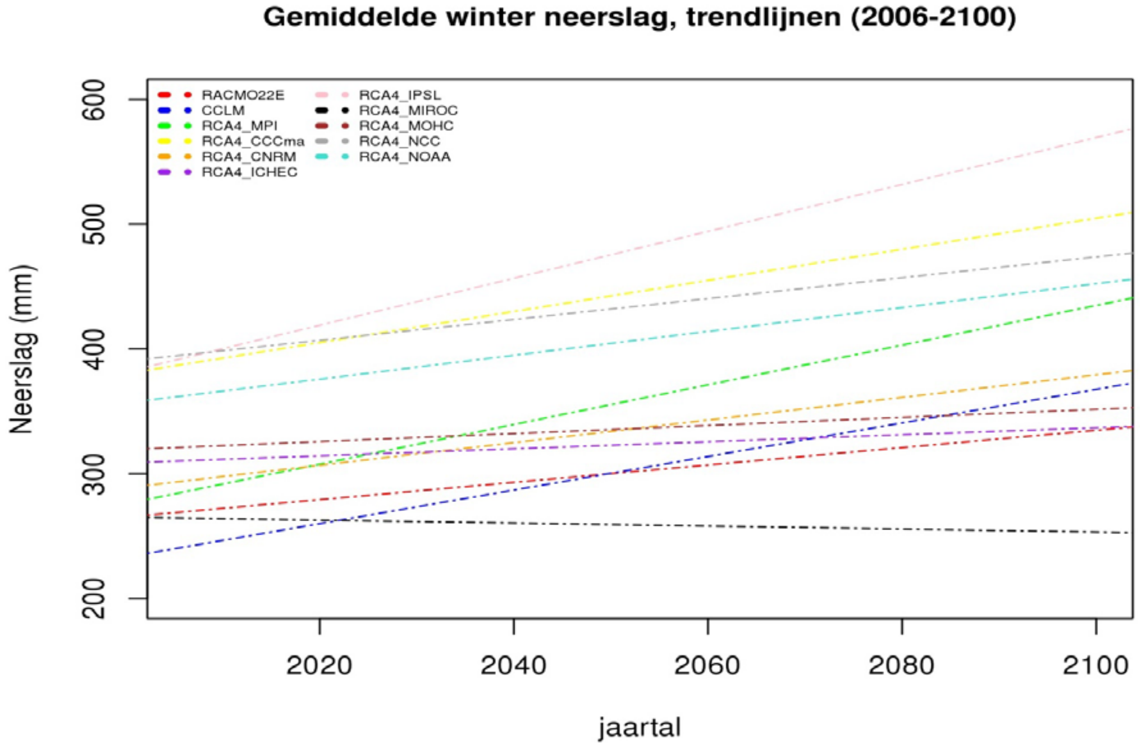


Figure 9: Mean winter precipitation 2006-2100 (RCP8.5), trend lines

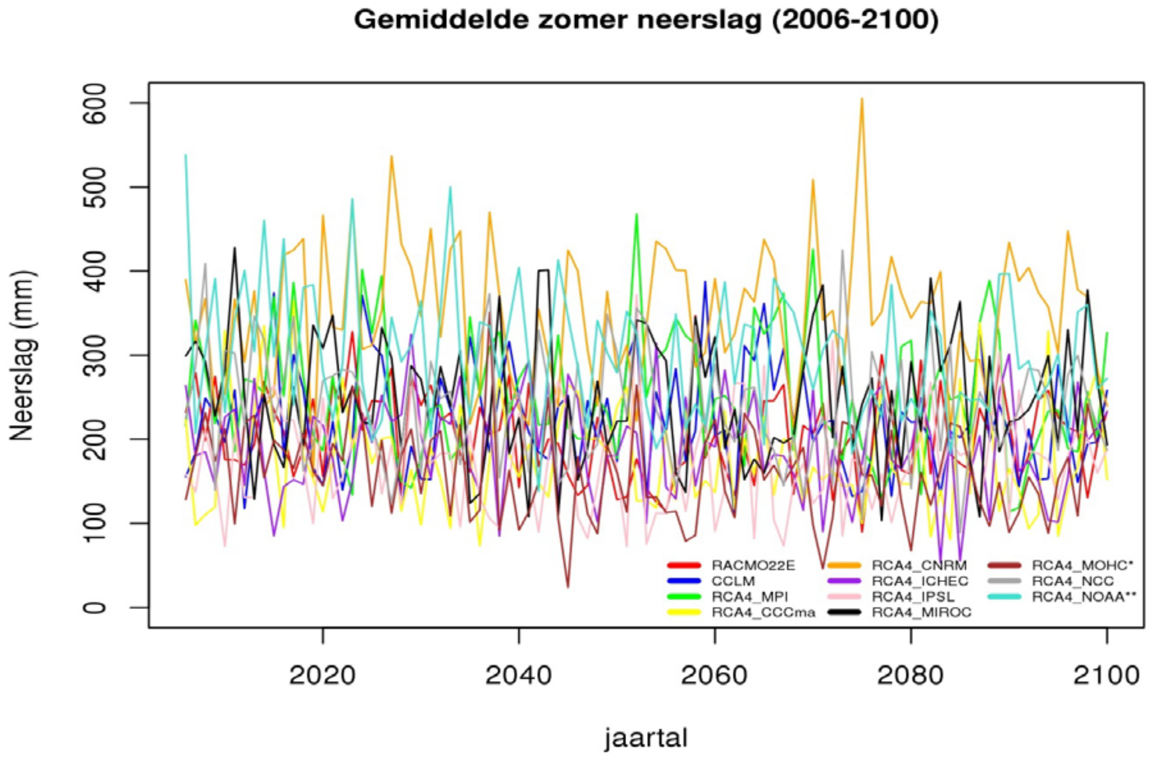
Table 6: Mean winter precipitation change (mm) per 100 years for every model (RCP8.5)

model	ΔPw/100 years(mm) (method 1)	ΔPw/100 years (mm) (method 2)	ΔPw/100 years (mm) (method 3)
CCLM	134.5	114.28	70.32
RACMO22E	69.58	-36.17	27.69
RCA4 CCCma***	124.6	179.29	80.92
RCA4 CNRM***	90.6	34.04	60.05
RCA4 ICHEC	281.9	260.04	61.77
RCA4 IPSL	188	169.58	172.66
RCA4 MIROC	-11.94	123.13	158.46
RCA4 MOHC	32.28	-53.38	-25.22
RCA4 MPI	159	129.63	82.86
RCA4 NCC**	83.53	-34.53	38.13
RCA4 NOAA	95.61	130.18	99.54
MACCBET	/	/	40.66

* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

3.3. Summer precipitation

For the RCP4.5 scenario nine of the eleven runs show a decrease in the amount of summer precipitation, but for only two of them the decrease is significant. For the RCP8.5 scenario ten of the eleven model runs show a decrease and seven of them are significant. For this scenario there is also one run that shows an significant increase in summer precipitation. By the end of this century the amount of summer precipitation for Belgium will probably decrease.



* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

Figure 10: Mean summer precipitation 2006-2100 (RCP4.5)

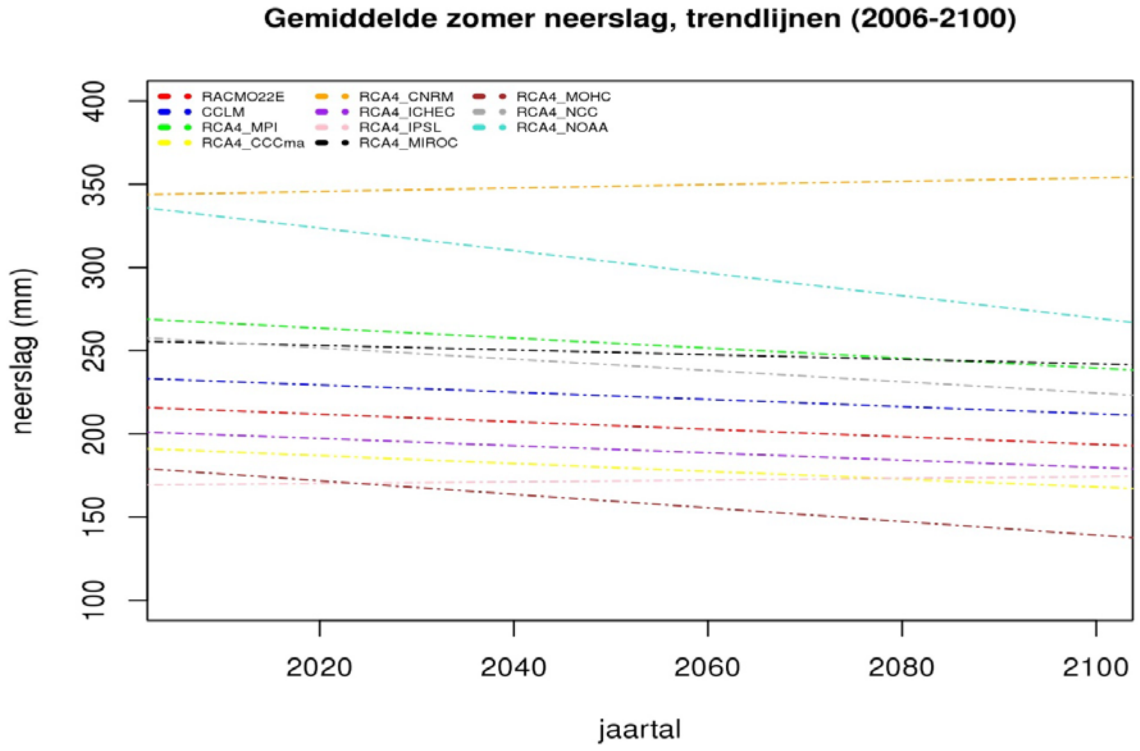
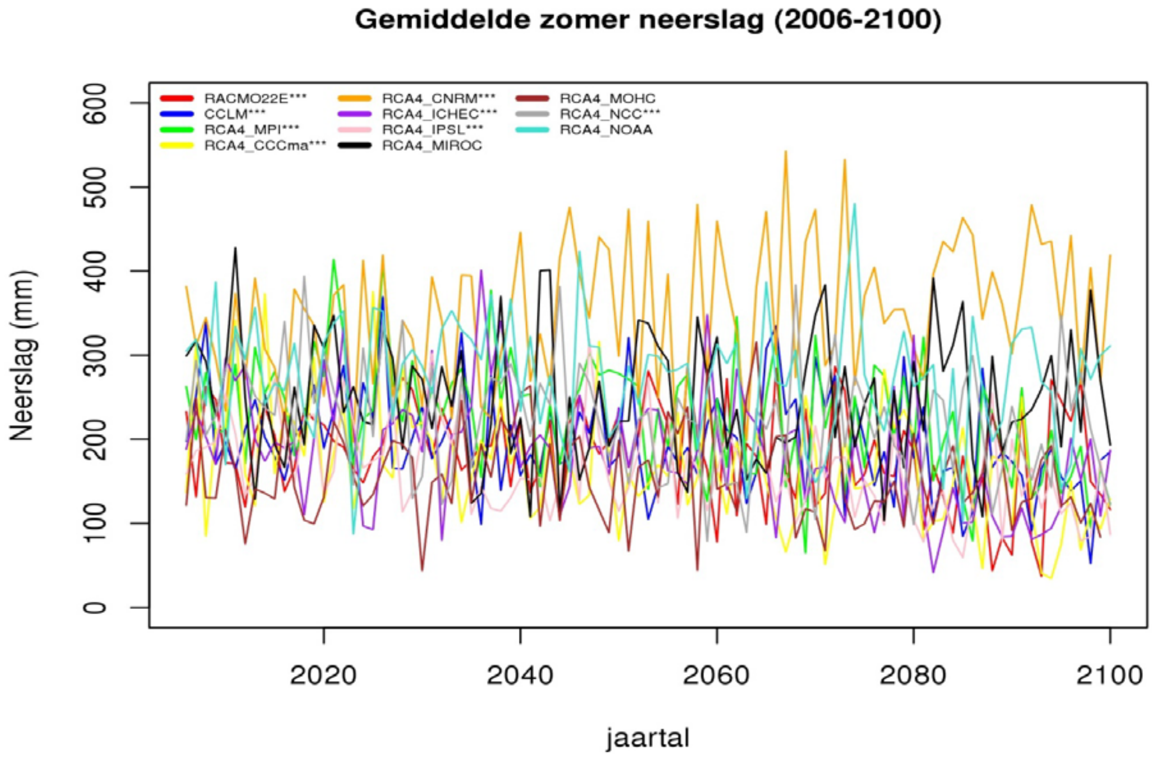


Figure 11: Mean summer precipitation 2006-2100 (RCP4.5), trend lines

Table 7: Mean summer precipitation change (mm) per 100 years for every model (RCP4.5)

model	ΔPz/100 years (mm) (method 1)	ΔPz/100 years (mm) (method 2)	ΔPz/100 years (mm) (method 3)
CCLM	-21.66	83.56	21.85
RACMO22E	2.1	80.43	-5.05
RCA4 CCCma	-23.5	-116.19	-61.6
RCA4 CNRM	10.27	160.53	83.46
RCA4 ICHEC	-21.65	24.95	-53.36
RCA4 IPSL	5.07	-64.59	-15.43
RCA4 MIROC	-1.72	-148.94	-37.17
RCA4 MOHC*	-40.77	-70.23	-52.78
RCA4 MPI	-29.98	-46.35	18.97
RCA4 NCC	-33.82	-92.49	-109.18
RCA4 NOAA**	-67.68	-80.77	-79.8
MACCBET	/	-32.52	-32.86
ALARO	/	/	-40.24

* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant



* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

Figure 12: Mean summer precipitation 2006-2100 (RCP8.5)

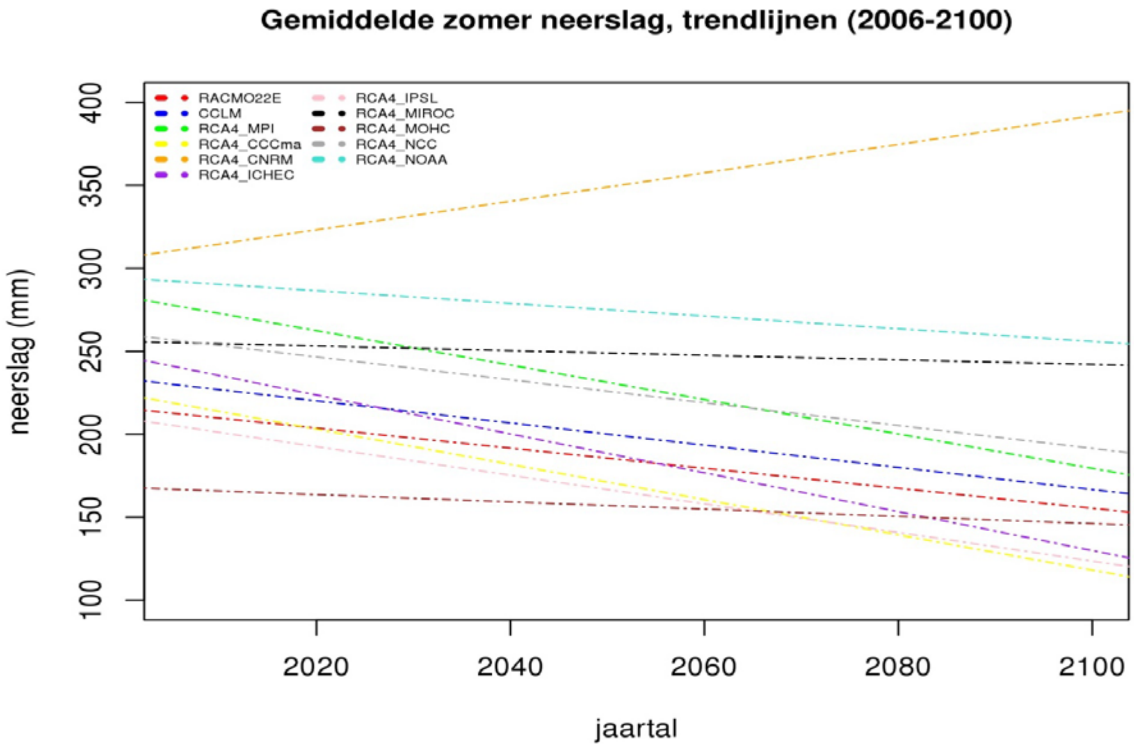


Figure 13: Mean summer precipitation 2006-2100 (RCP8.5), trend lines

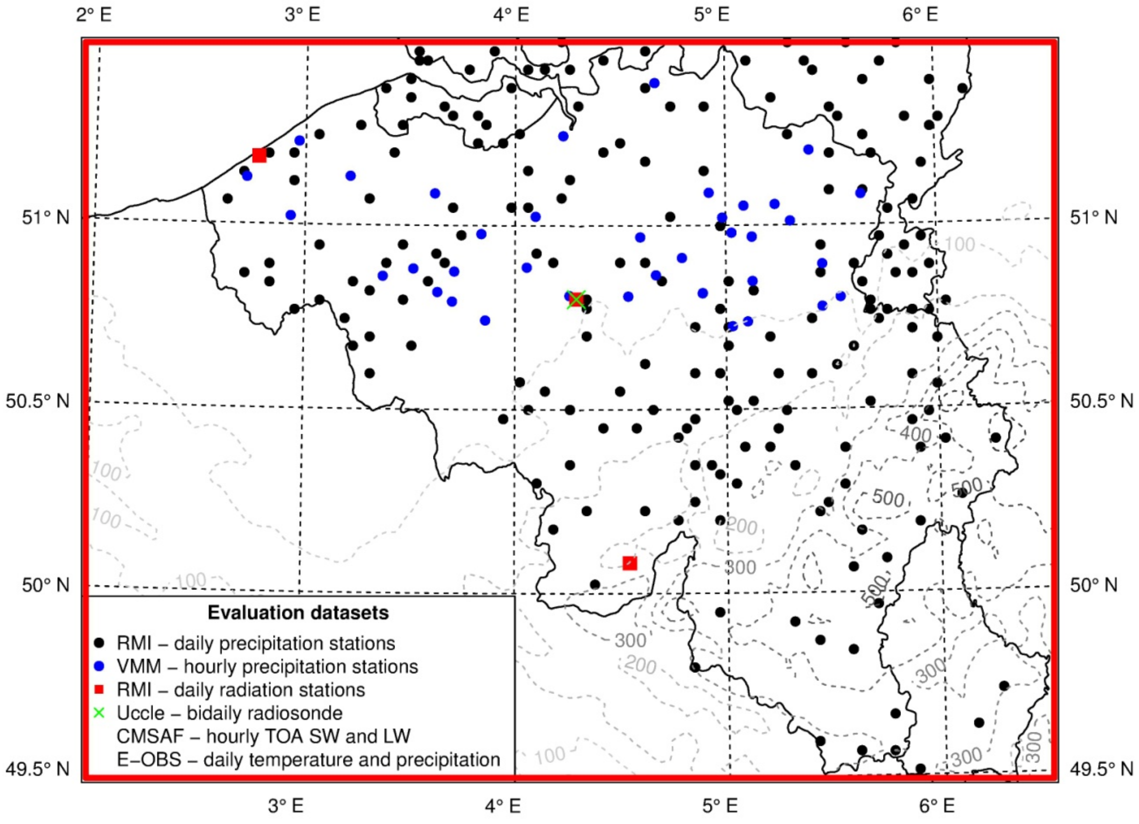
Table 8: Mean summer precipitation (mm) change per 100 years for every model (RCP8.5)

model	**ΔPz/100 years (mm) (method 1)**	**ΔPz/100 years (mm) (method 2)**	**ΔPz/100 years (mm) (method 3)**
CCLM	-66.92	-61.42	42.97
RACMO22E	-60.43	-14.31	-22.48
RCA4 CCCma	-106.3	-135.99	-124.27
RCA4 CNRM	85.8	46.56	118.26
RCA4 ICHEC	-117.2	107.50	-110.64
RCA4 IPSL	-86.23	-97.69	-79.48
RCA4 MIROC	-13.91	-2.62	-49.92
RCA4 MOHC*	-21.85	138.34	-7.66
RCA4 MPI	-103.7	59.73	-49.39
RCA4 NCC	-68.96	0.51	-34.27
RCA4 NOAA**	-38.23	85.33	-20.00
MACCBET	/	/	-43.58

* significant at level 0.1, ** significant at level 0.05, *** significant at level 0.01; all other runs are not significant

4. Evaluation of the MACCBET projection

An evaluation was performed using observations as presented in Figure 8. Daily values of precipitation (black points) are obtained from the Royal Meteorological Institute (RMI) of Belgium and from the Global Historical Climatology Network-Daily (GHCN-D) dataset (Menne et al., 2012). Only stations covering the full simulation period (2000-2010) are used resulting in 199 stations. Hourly values of precipitation (blue points) are derived from the Vlaamse Milieumaatschappij (VMM) dataset. In total 37 stations are available with a time-coverage of about 58 % of the simulation period. Hourly values of temperature were also extracted from the VMM dataset. However their spatial coverage is limited with only 8 stations mainly located in the Eastern part of the evaluation domain. This hourly temperature dataset covers about 58 % of the simulation period.

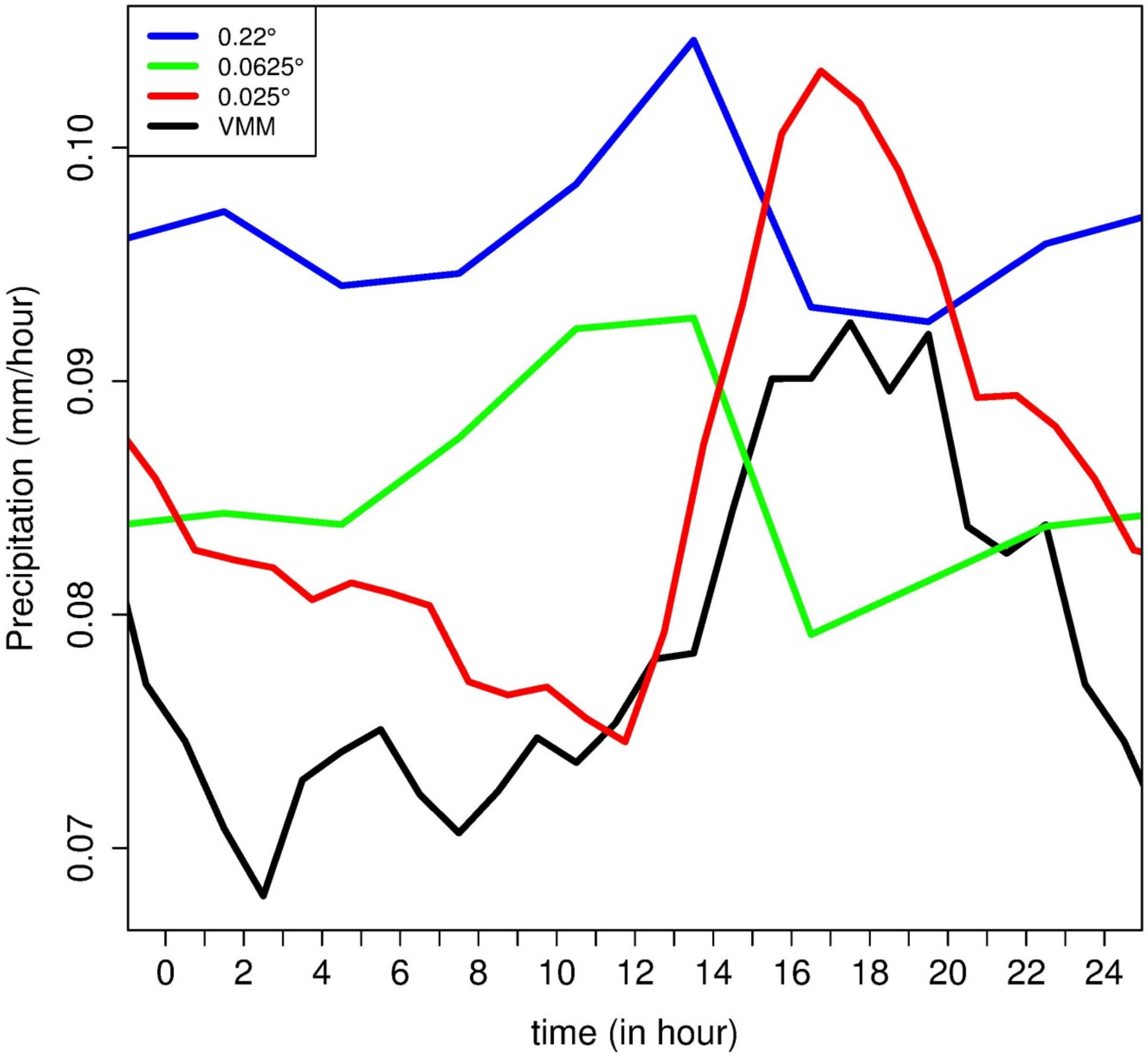


The black points indicate the RMI and GHCN-D stations (e.g. daily observations) while the red and blue points respectively indicate the locations of the temperature and precipitation stations extracted from the VMM dataset (e.g. hourly observations). In addition contour lines show the orography.

Figure 14: Map of the evaluation domain (red) together with the locations of the observational datasets

In addition to these stations, a gridded dataset is used in this evaluation, namely the gridded European observation dataset (E-OBS) version 7.0 (Haylock et al., 2008). Although temperature values derived from the VMM dataset are in agreement with E-OBS, based on RMI and GHCN-D datasets, E-OBS underestimates both the spatial and daily variability of precipitation. Indeed, the lower precipitation intensities are generally overestimated while the highest intensities are underestimated (not shown) Therefore, in this study, the use of precipitation extracted from the E-OBS dataset is restricted to the evaluation of spatial patterns or statistics on scales equal or greater than a month.

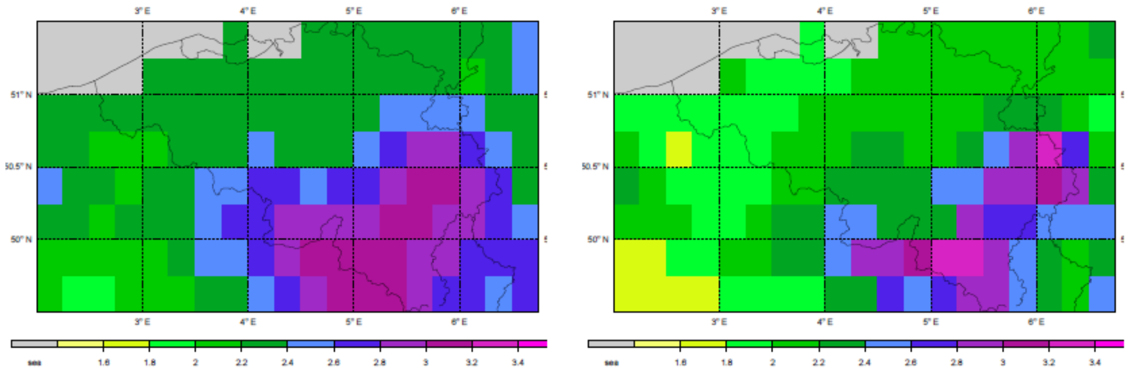
Kilometer-scale climate projections improve the representation of the timing of the precipitation daily cycle, which is observed to peak from 3 pm till 9 pm, due to convective activity. Although peaks of similar amplitude are modeled in the 25 km and 7 km simulations, the maximum intensity of these peaks occurs around 12 pm. The increase in resolution to 3 km shows a clear improvement in the timing of the convective peak, although an overestimation of the remains.



The simulations at 25 km (0.22˚), 7 km (0.625˚) and 3 km (0.025˚) and the VMM dataset are respectively shown in blue, green, red and black. The x-axis shows the local time (UTC +1).

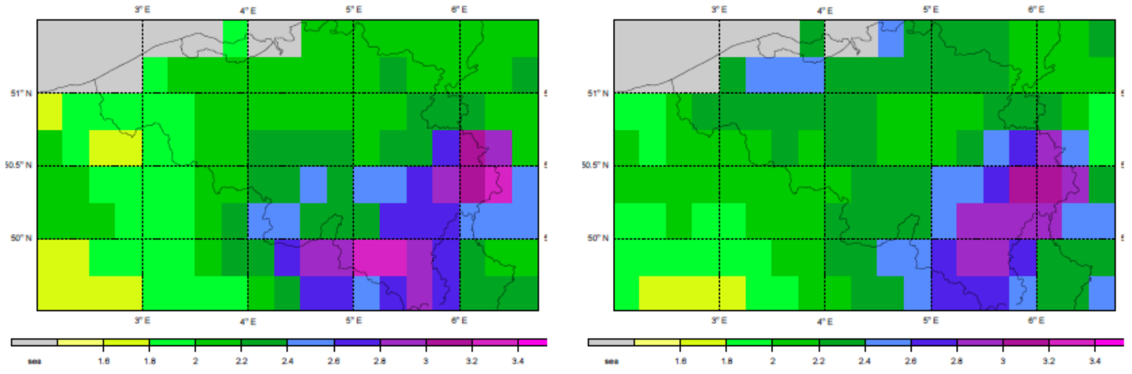
Figure 15: Daily cycle of hourly precipitation for the period 2000-2010

Increasing the resolution from 25 km to 7 km and 3 km results in an reduction of the average precipitation amounts and a reduction in model performance compared to the observations. This is mainly due to an overestimation of dry days of 10 % and 7 % in respectively the 7 km and 3 km model run. Although some small resolution dependencies appear in the flat areas (e.g. Western part of the domain), the main differences occur in the hilly area in the (South) East where precipitation amounts reach up to 3.4 mm/day. Indeed, the spatial extent of this area is largely overestimated in the coarser simulation (25 km) compared to the 3 and 7 km simulations.



(a) 0.22°

(b) 0.625°



(c) 0.025°

(d) E-OBS

Figure 16: Precipitation average over the period 2000-2010 for the EC-Earth driven simulations at (a) 25 km, (b) 7 km and (c) 3 km, all interpolated to the E-OBS dataset grid. The E-OBS dataset averaged over the period 2000-2010 is also displayed (d).

A better representation of extreme precipitation is found for the kilometer-scale climate projections during summer. Considering the entire year, the extremes are fairly well reproduced by all models (Table 9). In the summer period (June, July and August), when most of the convective activity occurs, higher precipitation intensity quantiles are observed compared to the statistics over the entire year. The representation of these quantiles, especially the 99th quantile, clearly improved when increasing the resolution from 25 km or 7 km to 3 km.

Table 9: Precipitation intensity average (mm, 95th and 99th quantiles for the observation and the simulations at 25 km (0.22˚), 7 km (0.625˚) and 3 km (0.025˚) for the full evaluation period and the summer period only

	full period (mm)			summer (mm)		
dataset	mean	95th	99th	mean	95th	99th
RMI (obs)	**2.45**	**12.00**	**23.00**	**2.73**	**14.30**	**27.70**
0.22°	2.45	11.8	21.48	2.20	11.18	22.64
0.0625°	2.17	10.98	20.9	1.94	10.28	23.01
0.025°	2.18	11.18	21.73	2.07	11.61	26.64

This inter-station variance is usually improved in the kilometer-scale simulations compared to the coarser resolution, due to the local character of convective precipitation. The highest variance quantiles, that characterizes local and intense precipitation events typical of convective events are also largely improved in the kilometer-scale simulation. Indeed the 95th percentile of the inter-station variability reaches 43 mm^2 day^{-2} 3 km simulation against the observed 49 mm^2 day^{-2}, while the 25 km and 7 km simulations both have a score of 30 mm^2 day^{-2}.

Table 10: Daily inter-station variance average, 95th and 99th quantiles for the observation and the different simulations for the full evaluation period and the summer period only

	full period (mm)			summer (mm)		
datasets	mean	95th	99th	mean	95th	99th
RMI (obs)	**10.47**	**48.66**	**126.80**	**16.74**	**84.10**	**221.35**
0.22°	7.21	30.15	92.81	11.84	43.52	163.90
0.0625°	7.51	30.41	123.21	12.94	49.93	219.77
0.025°	9.28	42.59	123.80	17.02	84.10	221.87

5. Comparison of Belgian versus CORDEX projections

We use the climate sensitivity to look where the 3 km resolution MACCBET runs and the 4 km ALARO run are located in the ensemble of the 50 km resolution CORDEX runs for both RCP scenarios. The climate sensitivity is the mean increase or decrease of a variable (ex. Temperature) over a period of 100 years. To measure this climate sensitivity two approaches were used for the MACCBET runs (for the RCP8.5 scenario only the second approach), one approach for the ALARO run and three for the CORDEX runs. For the MACCBET runs the difference was taken between period 2 and the control period and the difference between period 3 and the control period (see section 2.2). Both values were then rescaled to a period of 100 years. For the ALARO run the difference was taken between the future period (2071-2100) and the historic period (1961-1990) and rescaled to a period of 100 years. For the CORDEX runs the same two approaches were used but the control period (period 1) goes from 2006 till 2015, period 2 from 2031 till 2040 and period 3 from 2065 till 2074. The third approach is al linear regression because for the CORDEX runs continuous data is available from 2006 till 2100. The approaches for the different climate runs are given in table 11.

Table 11: Approaches for climate sensitivity

climate model	1st approach	2nd approach	3rd approach
MACCBET	((FUT2030_RCP4.5-PRES_EC)/25)*100	((FUT2064_RCP4.5-PRES_EC)/59)*100	/
ALARO	/	((FUT2085_A1B-HIST_ERA)/110)*100	/
CORDEX	(((2031-2040)-(2006-2015))/25)*100	(((2065-2074)-(2006-2015))/59)*100	linear regression

5.1. Temperature

For the CORDEX runs (RCP4.5) the mean climate sensitivity lies between 1.5 and 2 °C per 100 years. For the FUT2030_RCP4.5 run of MACCBET the climate sensitivity is 4.32 °C per 100 years. The temperature for the FUT2030_RCP4.5 run is at the higher end of the ensemble. This is also the case for the FUT2085_A1B run of ALARO, with a climate sensitivity of 2.58 °C per 100 years. The FUT2064_RCP4.5 run shows a climate sensitivity of 1.14 °C per 100 years. The temperature for this run is situated at the lower end of the ensemble.

The mean climate sensitivity for the RCP8.5 scenario lies higher than that one of the RCP4.5 scenario. The FUT2064_RCP8.5 run has a mean climate sensitivity of 2.24 °C per 100 years. The temperature for this run is situated at the lower end of the ensemble because the mean climate sensitivity for the CORDEX runs lies around 3.5 °C per 100 years.

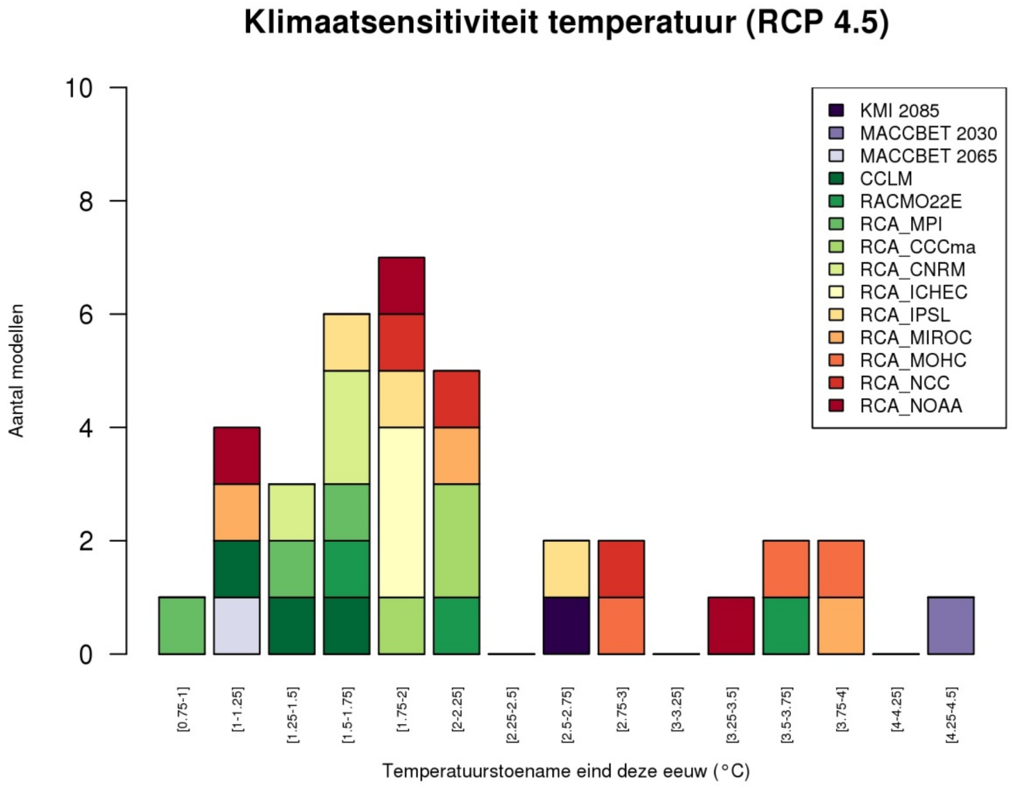


Figure 17: Temperature increase for Uccle by the end of the century (RCP4.5)

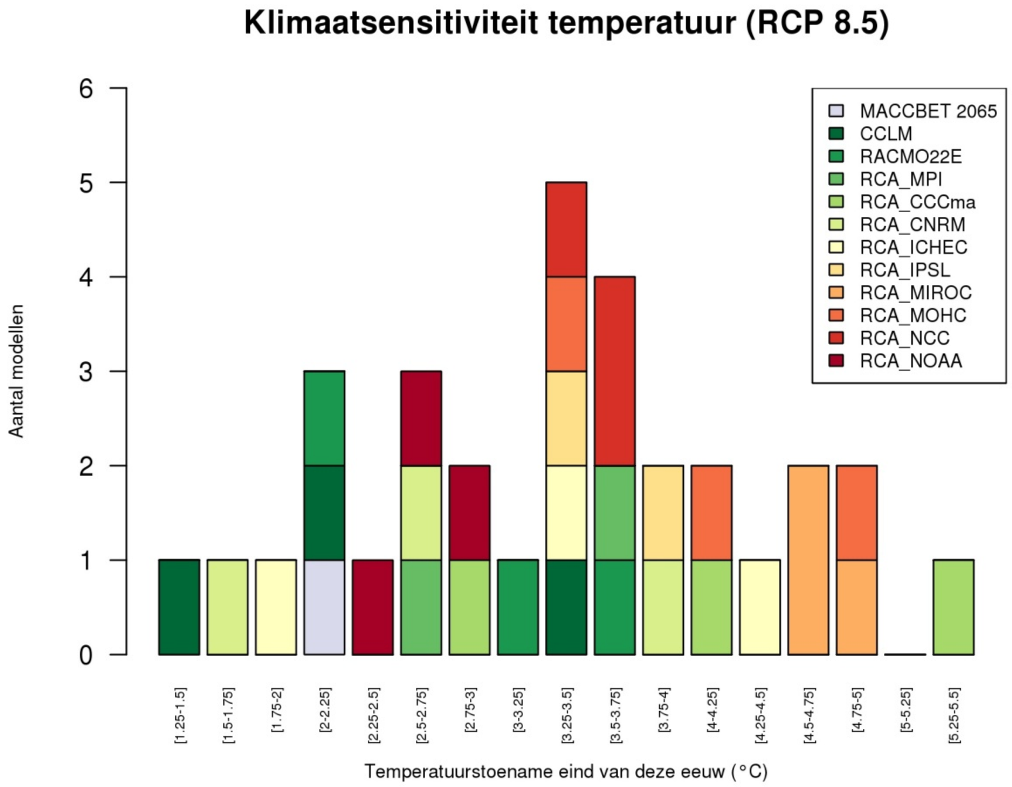


Figure 18: Temperature increase for Uccle by the end of the century (RCP8.5)

5.2. Yearly precipitation

The mean climate sensitivity of the CORDEX runs for yearly precipitation lies between -100 mm en 100 mm per 100 years. The FUT2030_RCP4.5 run of MACCBET has a mean climate sensitivity of -221.5 mm per 100 years, while the FUT2064_RCP4.5 run has a mean climate sensitivity of -11.13 mm per 100 years. Like the temperature, the yearly precipitation for the FUT2064_RCP4.5 run shows a better agreement with the CORDEX runs than the FUT2030_RCP4.5 run. The FUT2085_A1B has a climate sensitivity of -0.21 mm and lies in the middle of the CORDEX ensemble.

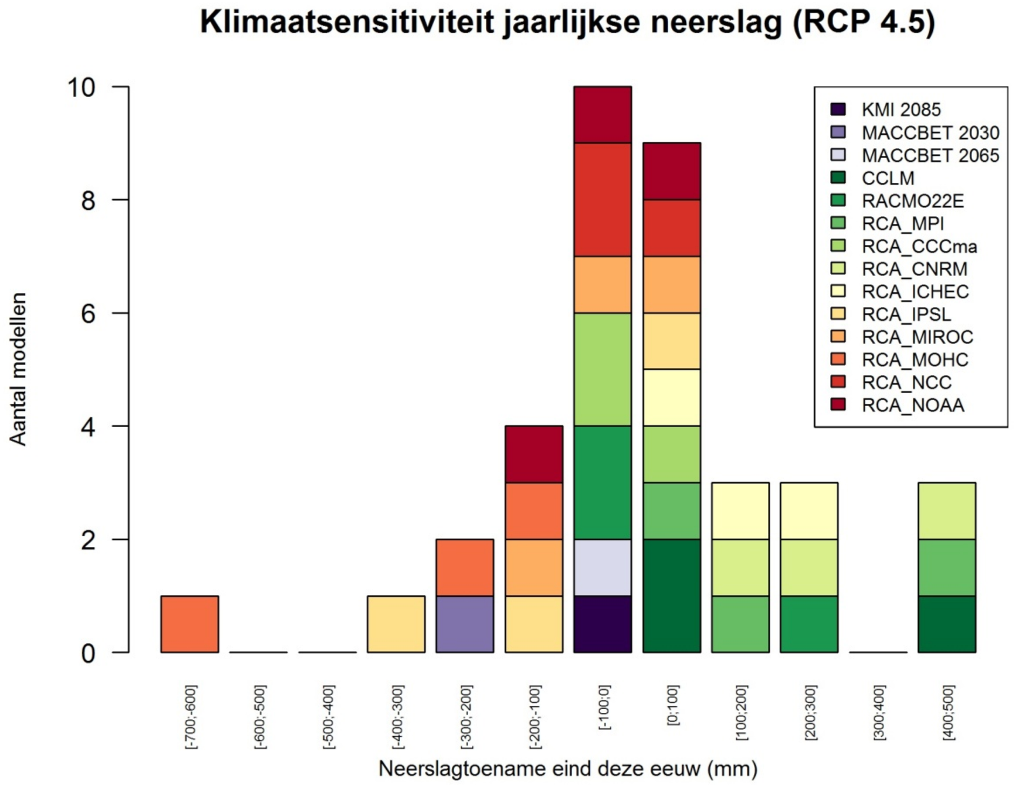


Figure 19: Change in yearly precipitation for Uccle by the end of the century (RCP4.5)

5.3. Winter precipitation

The biggest differences for precipitation in the future are expected during winter and summer. An increase is expected for the amount of precipitation in the winter and a decrease for the amount in the summer. The CORDEX runs show a mean climate sensitivity between 0 and 50 mm per 100 years for winter precipitation for the RCP4.5 scenario. The FUT2085_A1B lies in the middle of the CORDEX ensemble with a climate sensitivity of 3.94 mm per 100 years. Both MACCBET runs model a small decrease in winter precipitation, with a climate sensitivity of -0.44 mm and -3.68 mm per 100 years. The FUT2065_RCP8.5 run shows an increase in winter precipitation of 40.66 mm per 100 years in accordance with the expectations. The CORDEX runs show a mean climate sensitivity between 50 and 100 mm per 100 years for winter precipitation for the RCP8.5 scenario.

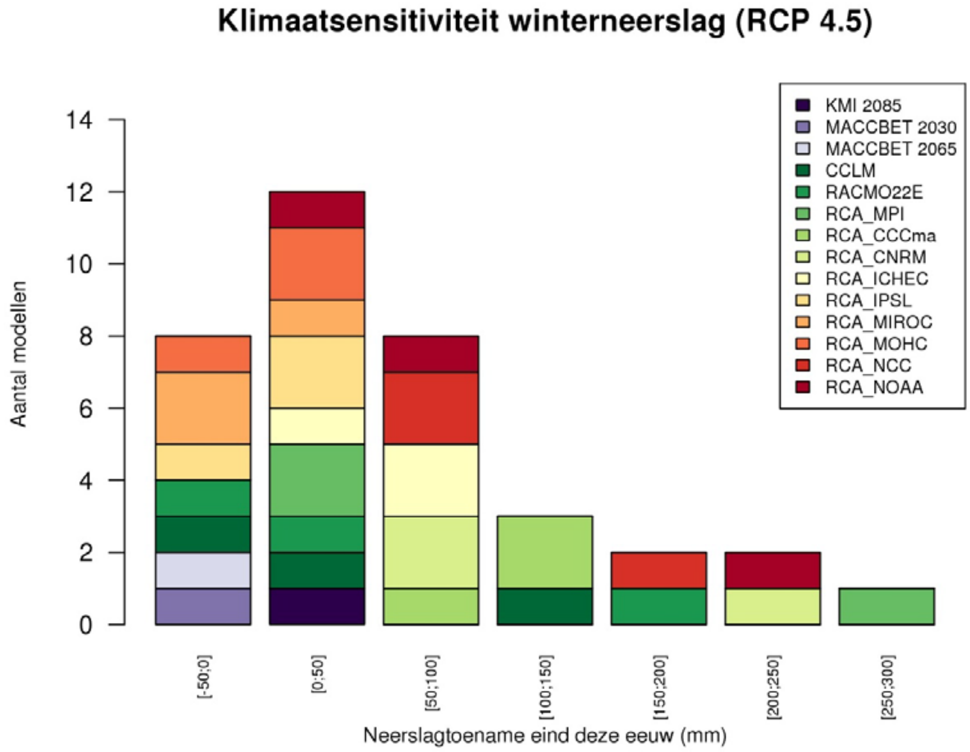


Figure 20: Change in winter precipitation for Uccle by the end of the century (RCP4.5)

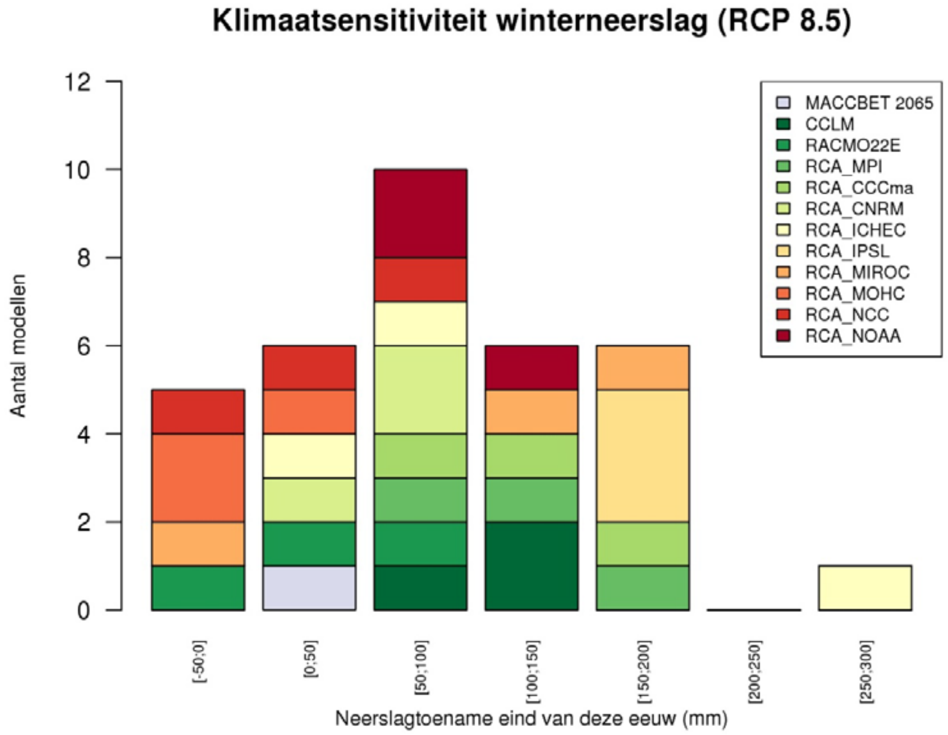


Figure 21: Change in winter precipitation for Uccle by the end of the century (RCP8.5)

5.4. Summer precipitation

For the summer precipitation the mean climate sensitivity for the CORDEX runs (RCP4.5 and RCP8.5) lies between -50 and 0 mm per 100 years. Also the three MACCBET runs (-32.52 mm, -32.86 mm and -43.58 mm) and the ALARO run (-40.24 mm) are lying in this interval. The MACCBET runs and the ALARO run are lying in the middle of the CORDEX ensemble.

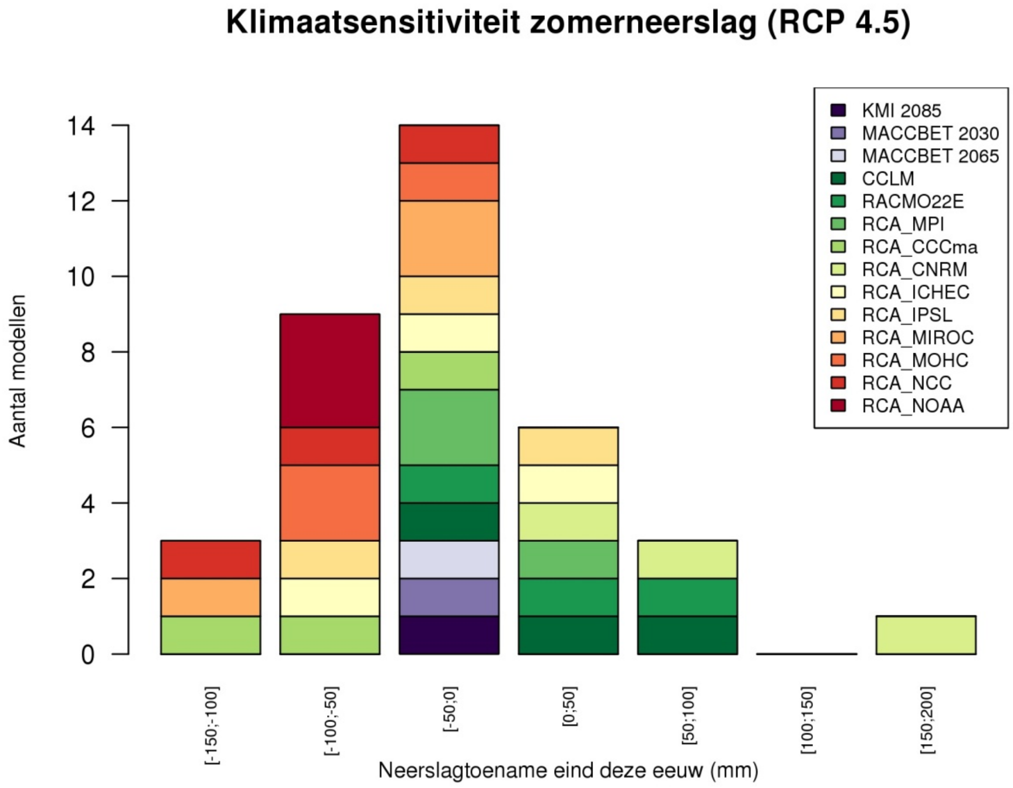


Figure 22: Change in summer precipitation for Uccle by the end of the century (RCP4.5)

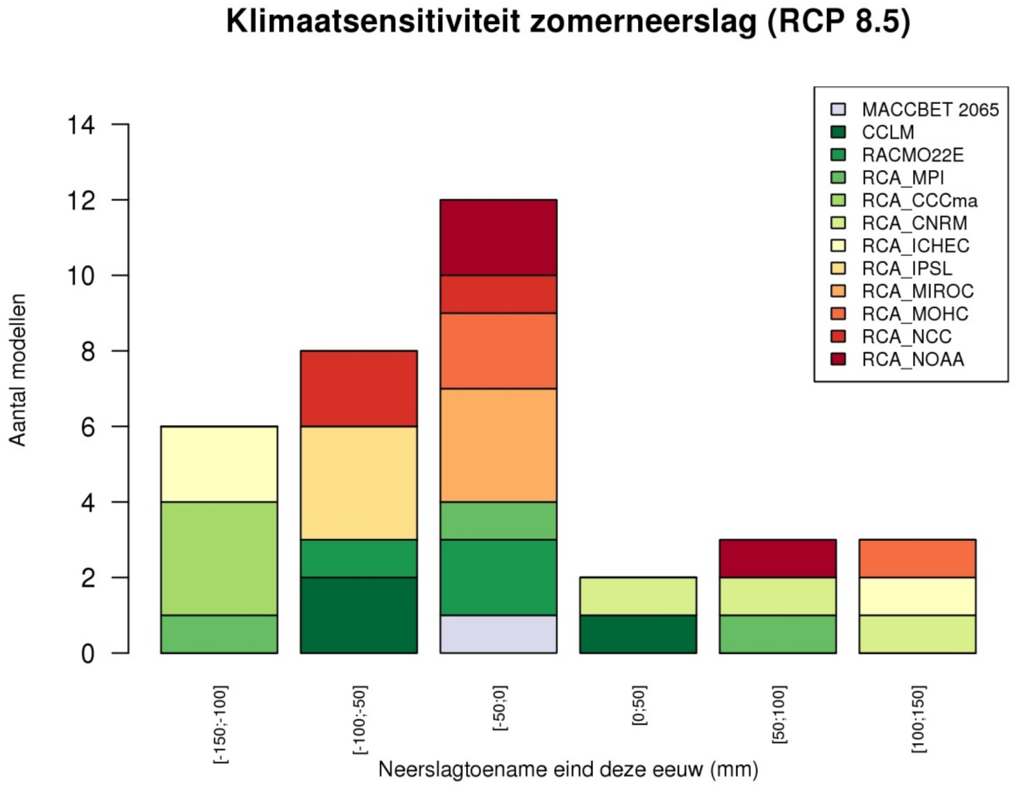


Figure 23: Change in summer precipitation for Uccle by the end of the century (RCP8.5)

6. Belgian model projections for extremes in Uccle

For the MACCBET model projections only the RCP8.5 scenario (FUT2064_RCP8.5 run) was used. This scenario is lying for temperature and precipitation in the middle of the CORDEX ensemble. It is important to know that these results are only results from one member of the ensemble, so be careful with the interpretation of these data.

According to the FUT2064_RCP8.5 run of MACCBET a temperature increase of 2.24 °C can be expected by the end of the century. The summer temperature will increase stronger than the winter temperature. For the summer temperature an increase of 3.05 °C per 100 years was modelled, for the winter temperature an increase of 2.03 °C per 100 years. The projection for the amount of precipitation in the winter shows an increase and the projection for the amount of precipitation in the summer shows a decrease by the year 2100. The increase and decrease are of the same order, +40.66 mm in the winter and -43.58 mm in the summer.

These changes in temperature and precipitation are expected to have an influence on the frequency of extreme events, which are of great importance for policy makers. The changes in extreme events will be listed below:

- *Number of days above 25 °C and 30 °C*

  The number of days with a maximum temperature above 25 °C and 30 °C are a good measure for the number of heat waves. The total number of days was at every turn modelled for a period of 10 years.

  During the period 2001-2010 (PRES_EC) there were 262 days with a maximum temperature above 25 °C, during the period 2060-2069 (FUT2064_RCP8.5 run) there are already 446 days. This corresponds with an increase of 70 %. By the end of the century there are expected to be 573 days more in a period of 10 years with a maximum temperature above 25 °C, which corresponds with an increase of 119 % comparing to the period 2001-2010.

  Also for the number of days with a maximum temperature above 30 °C an increase is expected. During the period 2060-2069 (146 days) 92 more days with a maximum temperature above 30 °C were modelled than during the period 2001-2010 (54 days). By the end of the century there are expected to be already 155 days more in a period of 10 years, a tripling.

  Looking at these two parameters there can be concluded the amount of heat waves in Belgium is expected to increase strongly by the end of the century.

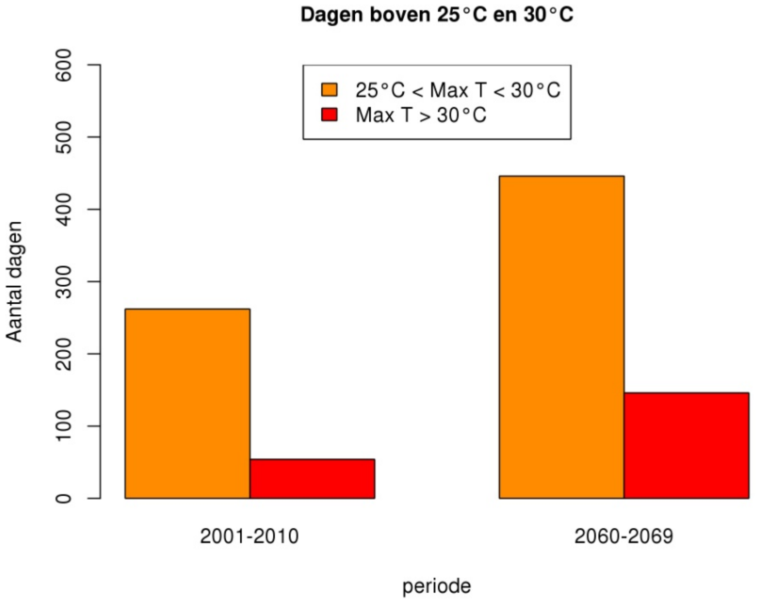


Figure 24: Number of days with a maximum temperature above 25 °C and 30 °C for two periods (2001-2010 and 2060-2069)

- *Number of days below 0 °C*

  To have an idea of the changes in the amount of cold waves, the total number of days with a minimum temperature below 0 °C and a maximum temperature below 0 °C was analyzed.

  Between 2001 and 2010 272 days were modelled with a minimum temperature below 0 °C. During the period 2060-2069 only 150 days were modelled, a decrease of 45 %. By the end of the century a decrease is expected of 76 %, so there are expected to be only 66 days with a minimum temperature below 0 °C in a period of 10 years.

  For the number of days with a maximum temperature below 0 °C a decrease of 55 % is expected by the end of the century.

  This shows the amount of cold waves in Belgium is expected to decrease in the future.

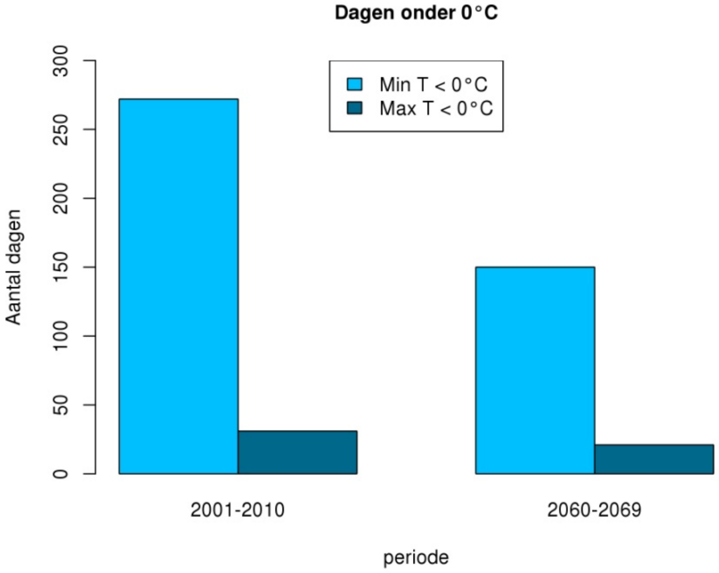


Figure 25: Number of days with a minimum temperature below 0 °C and number of days with a maximum temperature below 0 °C for two periods (2001-2010 and 2060-2069)

- *Number of dry days and wet days*

  A dry day is a day with a total daily precipitation smaller than 0.1 mm. A wet day is a day with a total daily precipitation equal or bigger than 0.1 mm.

  According to the MACCBET run the amount of dry days is expected increase in the future and the amount of wet days decreases. The amount of dry days in a period of 10 years is modelled to increase with 3 %, from 1 910 to 1 969 days, while the amount of wet days decreases with 3 %, from 1 742 to 1 684 days. By the end of the century the number of dry days is expected to increase with 5 % and the number of wet days decreases with 5 % comparing it with the period 2001-2010.

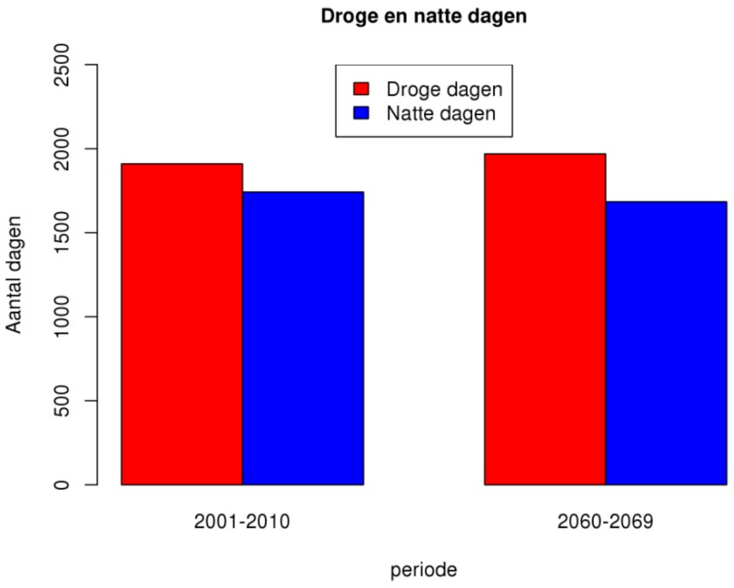


Figure 26: Number of dry and wet days for two periods (2001-2010 and 2060-2069)

- *Number of extreme drought events*

  When there are five consecutive dry days (five consecutive days with a daily precipitation below 0.1 mm) there is spoken of a drought event.

  As indicated above the amount of dry days is expected to increase in the future. Still the number of drought events is modelled to decrease. During the period 2001-2010 138 drought events were modelled. For the period 2060-2069 this number is 125, a decrease of 9 %. By the end of the century a decrease of 16 % is expected.

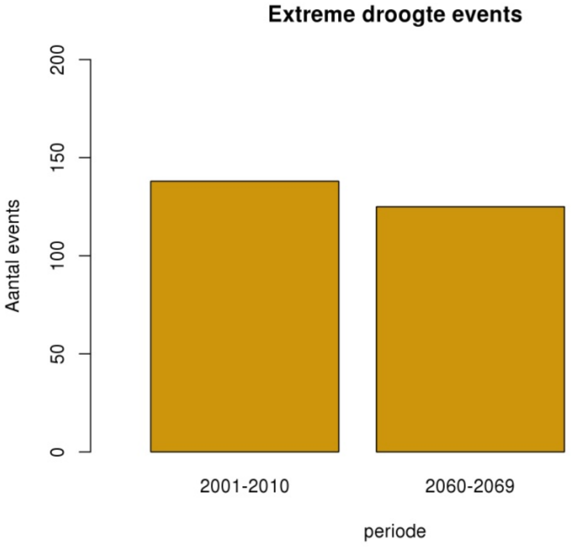


Figure 27: Number of extreme drought events for two periods (2001-2010 and 2060-2069)

- *Number of extreme precipitation events*

  An extreme precipitation day is a day with a total amount of precipitation above 10 mm.

  For Uccle an increase of 27 events (from 213 to 240) has been modelled for the period 2060-2069, comparing to the period 2001-2010. This corresponds with an increase of 12 %. If this continues 45 extreme precipitation events more are expected by the end of the century in a period of 10 years, which corresponds with an increase of 21 % comparing to the period 2001-2010.

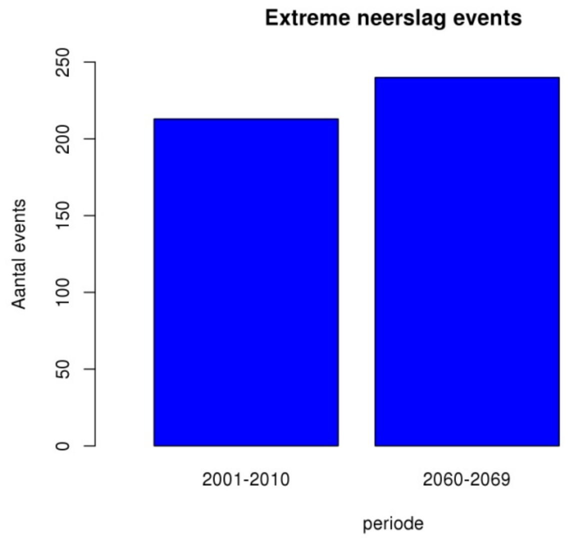


Figure 28: Number of extreme precipitation events for two periods (2001-2010 and 2060-2069)

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