The KNMI’14 $W_{H,dry}$ scenario for the Rhine and Meuse basins

Geert Lenderink and Jules Beersma

December 2015

KNMI Scientific Report WR 2015-02

Summary

We describe scenarios for the Rhine and Meuse catchments which are targeted to severe summer drought conditions that may occur in the future climate according to the global climate model simulations in CMIP5. With the release of the KNMI’14 scenarios it was realized that the potential decrease in summer precipitation was underestimated in particular for the Rhine catchment area, which was primarily a consequence of the followed methodology to produce the scenarios. Here, we present an additional climate scenario (that should be used in conjunction with the W_H scenario) which is in particular characterized by a stronger reduction of precipitation in summer. Averaged over the Rhine area this scenario (denoted as $W_{H,dry}$) has a decrease in summer precipitation of 17% in 2050 and 31% in 2085 (for the Meuse basin the decreases in summer in 2050 and 2085 are respectively 20 and 33%). This scenario corresponds roughly to the driest 10 % of the CMIP5 model simulations, and it can be used to estimate the consequences of potential of severe summer drought in the Rhine and Meuse basins under future climate conditions.

Contents

1. Introduction

In 2014 KNMI issued a new set of climate scenarios (Van den Hurk *et al.,* 2014; KNMI, 2015). The purpose of these scenarios is to represent possible pathways of future climate change that will enable society to prepare for, and adapt to, potential changes.

The backbone of the climate scenarios are the simulations of global climate models in CMIP5 (Coupled Model Intercomparison Project, phase 5). These consist of more than 200 simulations of global climate models, driven by different pathways of greenhouse gas concentrations, RCPs (representative concentration pathways). Despite the abundance of information from these global climate model simulations, the direct use of these simulations in applications is limited. This is the consequence of the lack of resolution, which is at best near 100 km in a global climate model, and also partly due to the limited availability of user relevant model output. The report of WG1 (working group 1) of the Intergovernmental panel on climate change (IPCC), dealing with the physics of climate change, is built to a large extend on the knowledge from these CMIP5 simulations. In the IPCC report regional climate change refers to regions as large as Northern Europe, or the Mediterranean. The report does not directly provide information for the Netherlands.

Therefore, in order to produce climate scenarios for the Netherlands further downscaling of the global climate simulations needs to be performed. For the climate scenarios we use a regional climate model, RACMO2. This model has been developed at KNMI, based on the physics of the ECMWF global weather prediction model, and the dynamical core of the HIRLAM limited area weather prediction model. The model has particularly good skill in comparison to other regional climate models in Europe (Christensen *et al.,* 2010). The model provides information at a grid of 12 km, an order of magnitude higher than the global climate models and also provides a very large set of output variables.

RACMO cannot be run to downscale all the results of the CMIP5 simulations due to technical and computational demands. A regional climate model simulation of 150 year typically takes one (small domain) to a few months (large European wide domain) on the high performance computer at KNMI. Also the information from a global climate model to force the regional climate model is only available for a limited subset of the CMIP5 ensemble.

To produce the KNMI scenarios we therefore used a method in which a set of eight simulations of RACMO, forced by the global climate model EC-Earth, is further post processed. This post processing consists of a selection of the model output based on the global temperature rise, and a resampling of model output to represent primarily the uncertainty in the response of the atmospheric circulation to climate change. The method is discussed in detail in Lenderink *et al.* (2014). The method retains the full internal and physical consistency between the meteorological fields, both in time and in space, of the original model output. In principle, therefore the spatial pattern of changes can be provided, but note also that the spatial patterns of changes are not always systematic, in particular at small scales such as for instance for the Netherlands. This in contrast with the previous set of climate scenarios issued in 2006, in which there was no information on spatial patterns and only a limited number of (reasonably) consistent output variables (Lenderink *et al.,* 2007).

The KNMI scenarios have been optimized to represent the spread in seasonal mean temperature and precipitation changes in CMIP5 (when interpolated) for the Netherlands (Lenderink *et al.,* 2014). Although the scenarios have not been specifically designed for the Rhine catchment area, values of the changes can be derived from the spatial fields provided in the scenarios. This contrast with the KNMI'06 scenarios, in which there is no specific information for the Rhine catchment area due to the followed methodology to produce the scenarios, and the crude assumption was made (due to lack of alternatives) that the change for the Netherlands is representative for the Rhine too. To avoid this crude assumption in the new set of scenarios an improved method has been used in which the spatial field of changes can be derived.

However, evaluating the KNMI'14 scenarios for the Rhine catchment, it turns out that while the scenarios do cover potential decreases in rainfall in summer over the Netherlands rather well, the results averaged over the Rhine catchment area are less optimal. The CMIP5 model runs provide a range of possible changes in mean precipitation. With the set of four scenarios we intend to cover at least the 25 to 75 percentile range of the CMIP5 model outcomes for seasonal mean changes and preferably about the 10 to 90 percentile range (Lenderink *et al.,* 2014). The CMIP5 range is here determined by the model selection for the IPCC climate change Atlas (IPCC 2013: Annex I; see also climexp.knmi.nl/atlas). All model simulations driven by RCP4.5, RCP6 and RCP8.5, in total 106 simulations, have been given equal weights.

The most extreme KNMI'14 scenario in terms of summer drying is the W_H scenario. The mean change over the Netherland is -23 % in that scenario (Figure 1, right panel), which is between the 25th (-21 %) and 17th percentile (-26%) out of CMIP5 (Figure 1, left panel). For the Rhine catchment (upstream of Lobith) the CMIP5 target change is a decrease of about 30 % (left panel), while the set of RACMO2/EC-Earth simulations used for the W_H scenario (for the Netherlands) projects a decrease only halve as large (right panel).

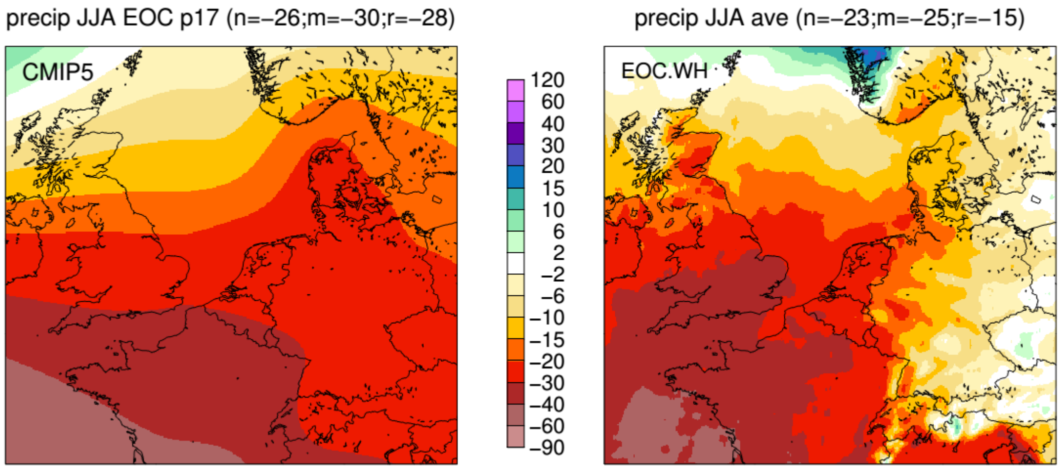

Figure 1. Response in mean summer precipitation compared to present-day climate (in % changes) in CMIP5 (left) and the W_H scenario (right). For CMIP5 the 17th percentile (i.e. the median or 50th percentile minus 1 standard deviation, assuming normally distributed data) of the distribution of changes derived from the CMIP5 model ensemble driven by emission scenarios RCP4.5, RCP6 and RCP8.5, all with equal weight) (data from climexp.knmi.nl/atlas). Changes averaged over the Netherlands (n), the Meuse catchment (upstream of Maastricht) (m) and the Rhine catchment (upstream of Lobith) (r) are given in the panel titles.

There are two reasons for decreases in summer precipitation over south western and southern Europe, one is primarily dynamical and related to the increase in mean sea level pressure over the British Isles. The causes of this anomalous high pressure system are not entirely proven, but it appears that the lag of temperature increase over the Atlantic ocean plays a crucial role, possibly caused by the slowing down of the thermohaline ocean circulation. The other is primarily related to large scale continental drying of the soil and related feedbacks between clouds, radiation and precipitation. This feedback is very strong in a number of model simulations in CMIP5, but also relatively weak in others. The high pressure systems caused a drying of predominantly south western Europe, with an east-west gradient in precipitation response. The soil moisture feedback is related to a drying over the whole southern and central part of Europe, and ultimately causes a north-south gradient in precipitation response. It also appears that the occurrence of severe drying over the Mediterranean area causes an additional heat low response, with anomalous easterly winds over central Europe, transporting dry continental air westwards (Haarsma *et al.,* 2009). However, there is also evidence that the models that have the strongest soil moisture drying feedbacks are less realistic in the sense that they also display relative large biases (systematic errors) in the precipitation climatology for the present-day climate (Selten *et al.*, In preparation).

In the RACMO2-EC-Earth simulations used for the KNMI'14 scenarios the cause of the drying (that is, the reduction of precipitation) in summer is primarily related to the anomalous high pressure system over the British Isles (Lenderink *et al.,* 2014). The influence of this high pressure system decreases eastward, and this causes an east-west gradient in projected precipitation decrease. We note that south of the Alps the influence of large scale soil drying feedback is also visible. With the construction of the KNMI'14 scenarios, i.e. the resampling procedure employed to select sets of RACMO2-EC-Earth representative of each of the four scenarios, we primarily make use of variations in the strength of the anomalous high pressure system, and therefore primarily influence the strength of the drying in southwest Europe (Lenderink *et al.,* 2014). The east west gradient is however not influenced since it is a persistent characteristic of the EC-Earth model.

Therefore, optimal results for the Rhine area could not be obtained with the chosen method while simultaneously retaining the required results for the Netherlands. In essence, this is a consequence of downscaling only one global climate model (that is, EC-Earth), which represents only one realization of the strength of large scale soil moisture feedbacks. The choice of the regional climate model, RACMO2, only plays a minor role here as the domain on which the model has been run is relatively small, and therefore these large scale feedbacks are almost entirely dominated by the global model.

We have attempted to produce a scenario by modifying the soil characteristics in EC-Earth and RACMO in order to promote large scale drying in summer. Although this method was to some extent successful, with the available resources we could not produce a scenario which is consistent with CMIP5 for both the middle as well as the end of this century as the large scale drying occurred too late in the century in those simulations.

In this report we will therefore discuss the outcome of an alternative method to produce a scenario that is tailored to represent the potential of a relatively strong drying in summer over the Rhine catchment as indicated by the range spanned by the CMIP5 model runs . This approach is based on the downscaling of a different CMIP5 model, HadGEM2-ES.

2. Runs with RACMO forced by HadGEM2-ES

Two RACMO2 simulations driven by HadGEM2-ES were performed. This global model is characterized by a strong drying response over southern Europe. RACMO2 has been run with standard physics, without adaptations in the soil scheme. Two members of HadGEM2-ES using RCP8.5 are downscaled, r1i1p1 and r2i1p1.

Again, we consider the climate change signal at a 3.5 °C global warming, which is the steering value used for the KNMI'14 scenarios for 2085. In HadGEM2-ES this value of global warming is reached rather early in the century, in the period 2056-2085. For 2050 the global warming is 2 °C, which is equivalent to the period 2031-2060 in HadGEM2-ES. For reasons explained below (in particular related to rather weak drying near the middle of the century) we use for 2050 a 5-year later period, that is 2036-2065 (which happens to be centered around 2050). The results are scenarios denoted by $W_{H,dry}$.

In the following we will refer to the scenario periods 2050 and 2085, and do not use the corresponding time periods of the model simulations. So, the $W_{H,dry}$ scenario for 2085 refers to the period 2056-2085 from the RACMO2-HadGEM2-ES results and $W_{H,dry}$ for 2050 refers to the period 2036-2065.

Winter and summer mean changes in the two scenarios, W_H (standard KNMI'14) and $W_{H,dry}$, for the Netherlands, the Meuse catchment (upstream of Maastricht) and the Rhine catchment (upstream of Lobith) can be found in the Tables in Appendix A. In these tables we also give the different percentiles of the distribution of CMIP5 results.

For winter we aim to be close to the 90th percentile of the distribution in CMIP5, where we take into account the 106 simulations that are contained in the IPCC atlas using RCP4.5, RCP6 and RCP8.5. The target range is between the 83th and the 95th percentile. For summer we do not trust the highest values of drying sufficiently and we limit the target range to 10-17th percentile. In the text we will use CMIP5 PX when referring to the Xth percentile of the CMIP5 model simulations used for the atlas.

2.1 Summer changes

For 2085 the response in mean summer precipitation in $W_{H,dry}$ (i.e. RACMO downscaling of HadGEM2-ES) over the Rhine catchment area of -31 % is much stronger than for W_H (Figure 2). The changes for the Netherlands is almost identical to the W_H scenario, while the response over the Rhine catchment area is approximately twice as large. For the Meuse catchment the $W_{H,dry}$ scenario is 8 % dryer than W_H. Also the pattern of changes over western Europe in $W_{H,dry}$ largely resembles the CMIP5 pattern for P10 and P17, which is in particular visible when the smaller spatial scales are filtered out (middle right panel). For the Rhine and Meuse catchments the response in $W_{H,dry}$ is between the P10 and P17 of CMIP5.

For 2050 the results for $W_{H,dry}$ are again within P10 to P17 range of CMIP5 (see Figure 3). The global mean warming in that period is 2.3 °C.

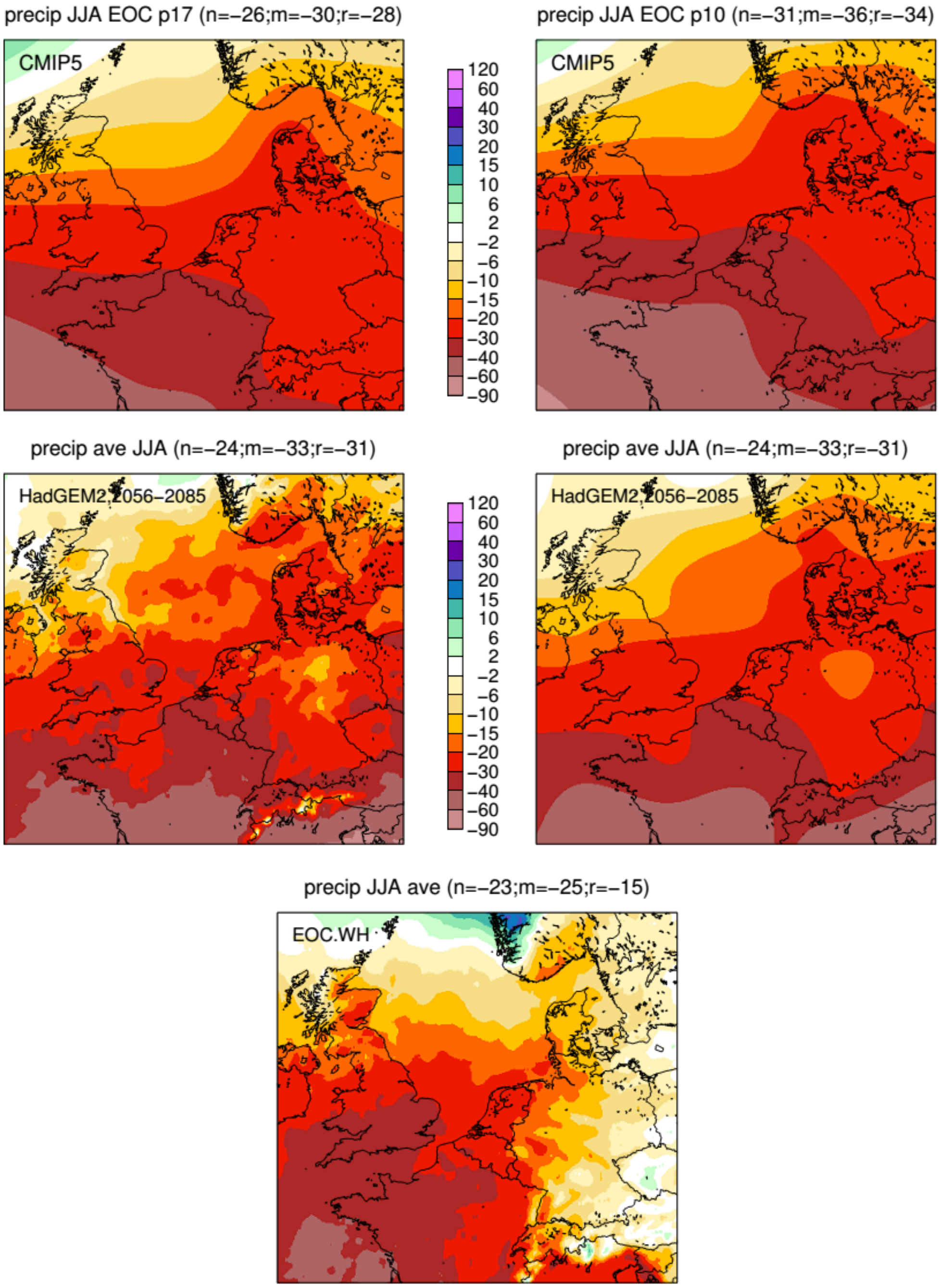

Figure 2. Response in mean summer (JJA) precipitation compared to present-day climate (in % changes). Upper panels CMIP5 (left, 17th percentile and right 10th percentile of the distribution of CMIP5 model simulations). Middle panels RACMO2 downscaling of HadGEM2-ES (left full signal, right signal spatially filtered to GCM scales) derived from 2056-2085 (period with 3.5 °C global warming), i.e. the $W_{H,dry}$ scenario. Lower panel, signal in the W_H scenario.

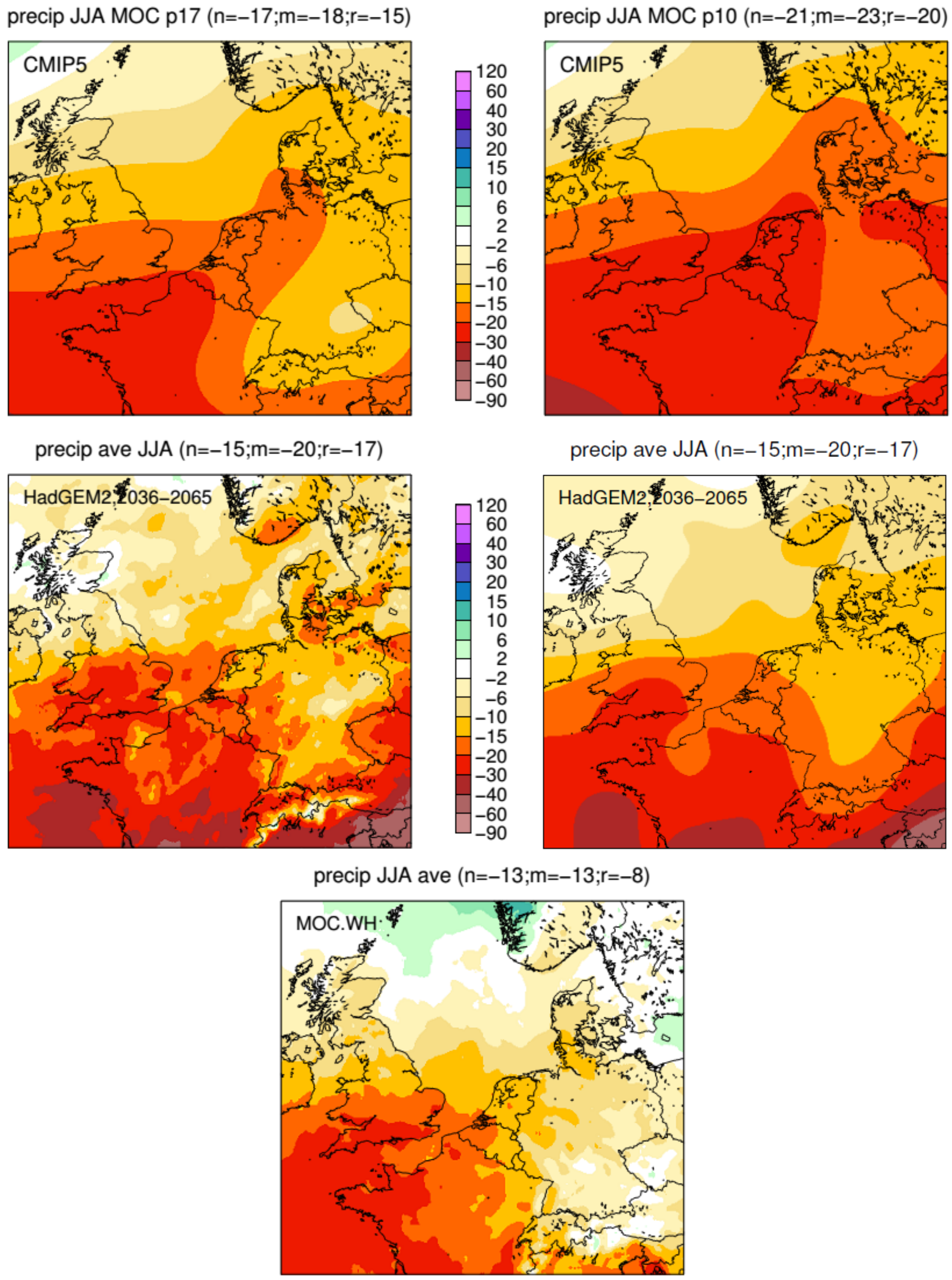

Figure 3. Similar to Figure 2, but now for the climate in 2050. For CMIP5 the 17th percentile (the median minus 1 standard deviation) and the 10th percentile are shown. Middle panels, the $W_{H,dry}$ scenario (RACMO2-HadGEM2), lower panel the W_H scenario.

The W_H scenario also underestimated the upper range of temperature changes from CMIP5. At the end of the century the projected changes are equal to the CMIP5 P75 (see Tables in Appendix A) for the Netherlands and the Rhine catchment area, and 0.2 °C above the this percentile for the Meuse catchment. In the new $W_{H,dry}$ scenario the temperature change is close to the CMIP5 P90 for the Rhine and Meuse. For the Netherlands the change is closer to the CMIP5 P83 (see Figure 4).

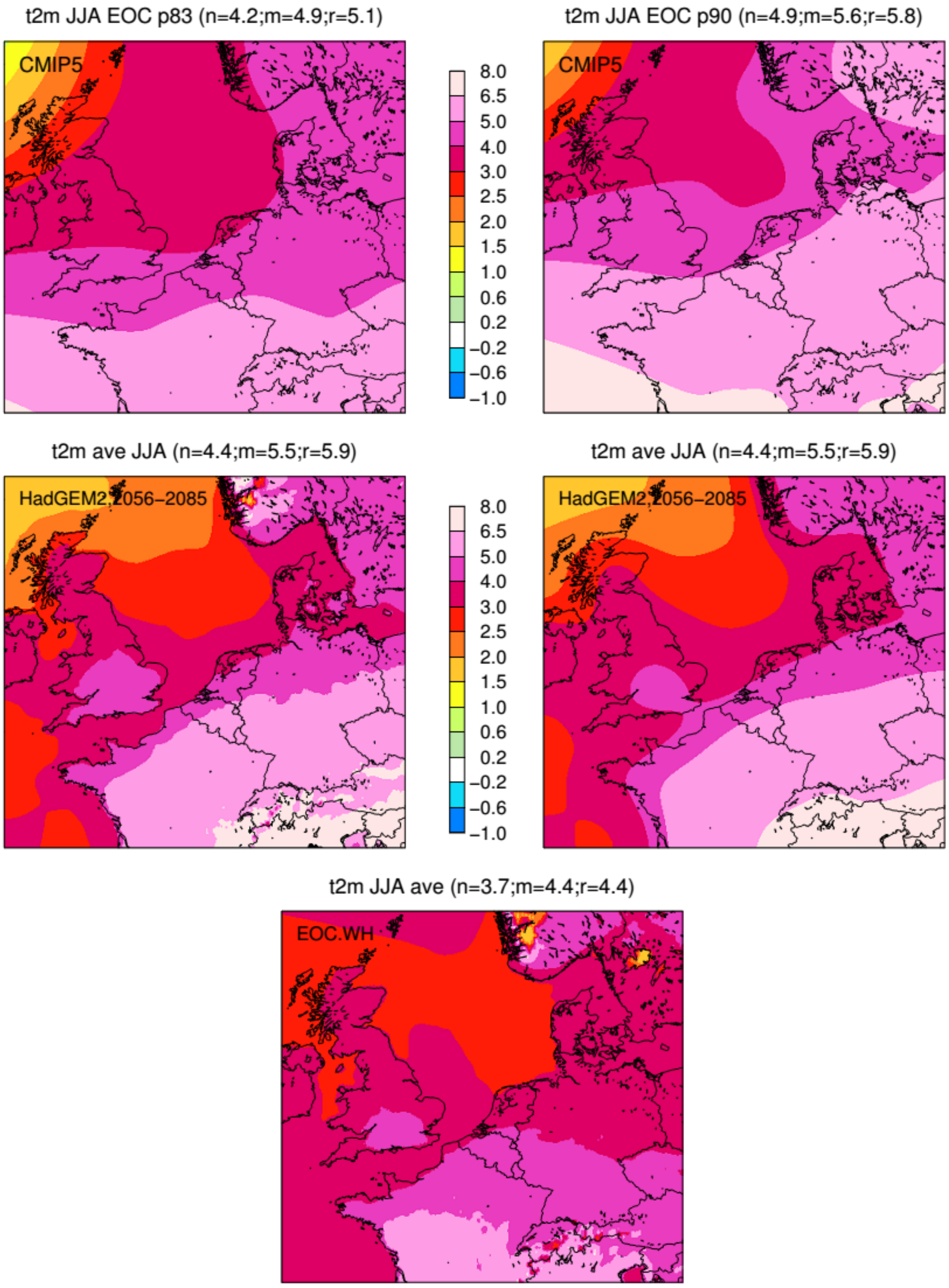

Figure 4. As Figure 2, but now for summer (JJA) temperature. For CMIP5 the 83th percentile (the median plus 1 standard deviation) and the 90th percentile are shown. Middle panels, the $W_{H,dry}$ scenario (RACMO2-HadGEM2), lower panel the W_H scenario.

It is also worthwhile to look at the changes in the distribution of relatively cold and warm months is summer, and likewise wet and dry months. We therefore look at three percentiles out of the distribution of monthly mean temperature and precipitation: the 10th percentile representing cold months (or dry months), the 50th percentile representing "average" months, and the 90th percentile representing warm (or wet) months.

The relative change in precipitation is much stronger for dry months than for average or wet months (Figure 5). This holds for both W_H and $W_{H,dry}$. Even for the relatively moderate W_H scenario the decrease in precipitation in dry months is about 40 %, while the decrease in the $W_{H,dry}$ scenario is approaching 80 %. The change in the 50th percentile is close to the change in mean summer precipitation, while the decrease in precipitation in wet months is considerably smaller.

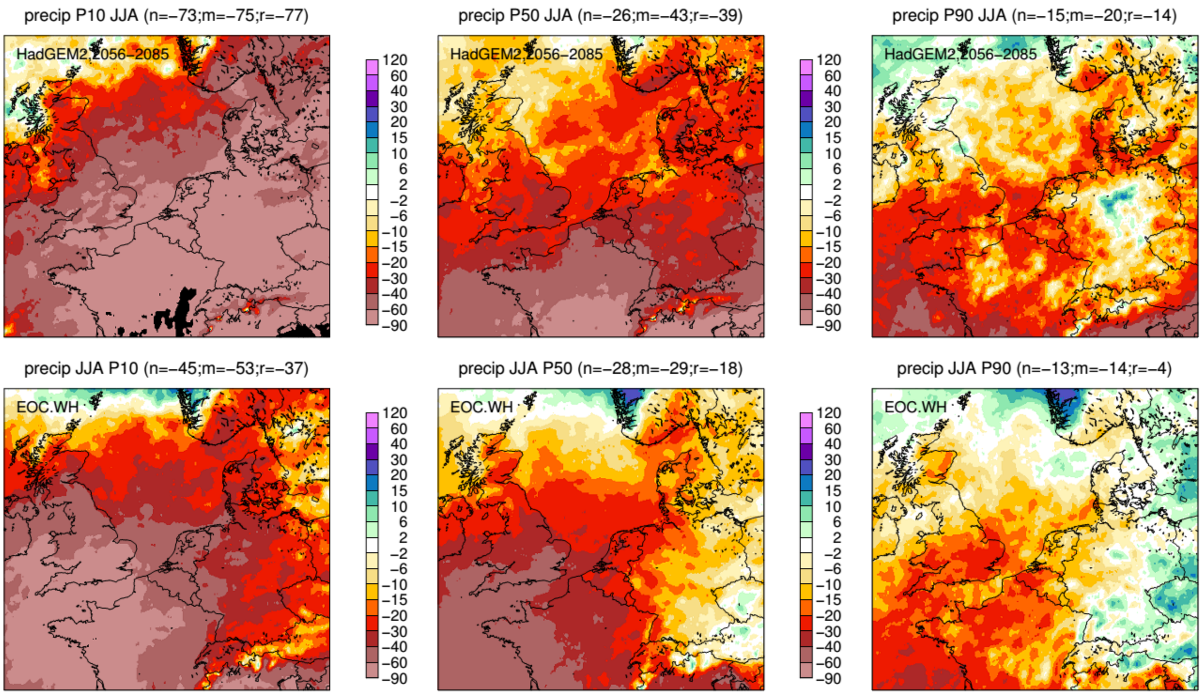

Figure 5. Change in 3 different percentiles of the distribution of monthly mean precipitation in summer (JJA), from left to right: the 10th percentiles (P10) representing dry months, the 50th percentile (P50) representing "average" months, and the 90th percentile (P90) representing wet months. Upper panels show the results for the $W_{H,dry}$ scenario (RACMO2-HadGEM2); lower panels the W_H scenario.

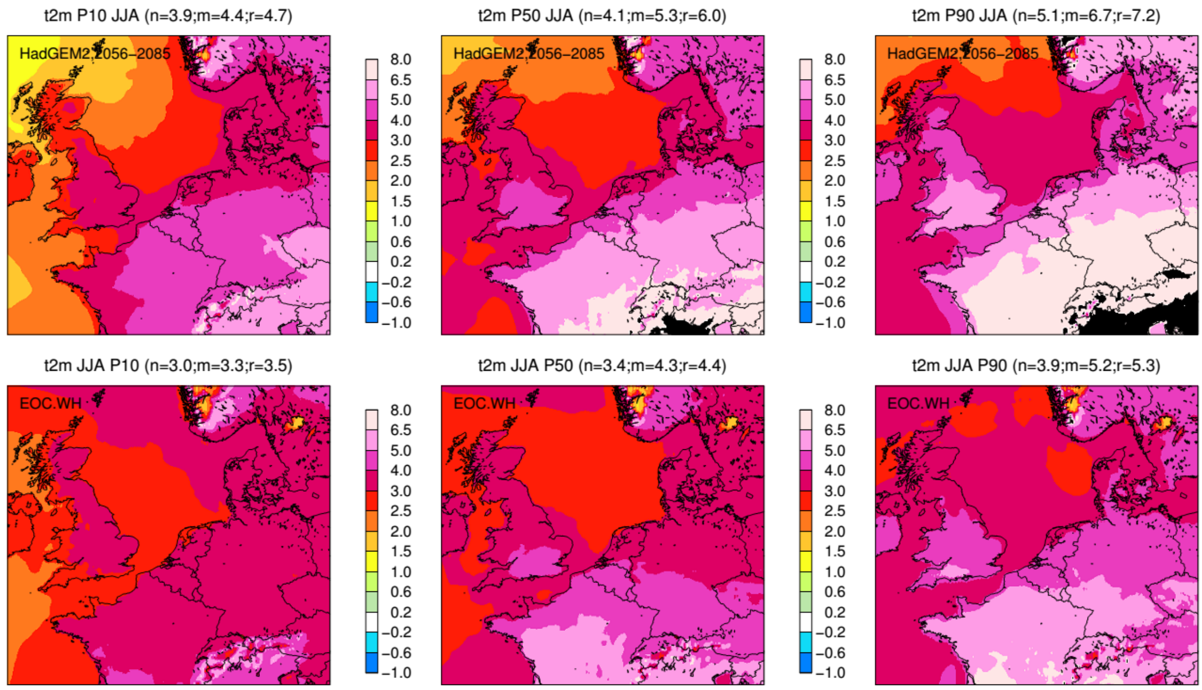

Figure 6. As figure 5, but now representing cold months (P10), "average" months (P50) and warm months (P90) in summer (JJA). Upper panels show the results for the $W_{H,dry}$ scenario (RACMO2-HadGEM2); lower panels the W_H scenario.

For summer temperatures temperature increases more for warm months, up to 7 °C for the $W_{H,dry}$ scenarios for the Rhine catchment area (Figure 6). An increase of 7 °C is twice as strong as the global mean temperature rise (of 3.5 °C by choice of the steering variable). For the Netherlands the temperature response is also stronger in the $W_{H,dry}$ scenario, although the mean temperature response does not reach the values in the previous set of scenarios: in KNMI'06 the mean summer response in the warmest scenario was 5.8 °C (at 4 °C global warming).

2.2 Winter changes

Here we consider the changes in winter precipitation, which are of relevance for the occurrence of wintertime discharge extremes. We note that in winter changes in precipitation extremes and changes in the means are similar when averaged over long enough time periods (see Appendix B). However, due to the long memory of the soil, changes in winter are also important for summertime drying. Figure 7 shows that both scenarios, W_H and $W_{H,dry}$, have an increase in mean winter precipitation, which is to be expected due to the increase in water vapour of the air with about 7 % per degree warming.

For the Netherlands, the increase in the new $W_{H,dry}$ scenario is approximately equal to the CMIP5 P75, which is a moderate, yet not very extreme scenario, and is below the required target range. In contrast, the W_H scenario is within the P90 to P95 range for the Netherlands which is in the target range. For the Rhine catchment the increase of 28% in mean winter precipitation is somewhat above the P95 of CMIP5 (which is +25%). The new $W_{H,dry}$ scenario is again close to the P75.

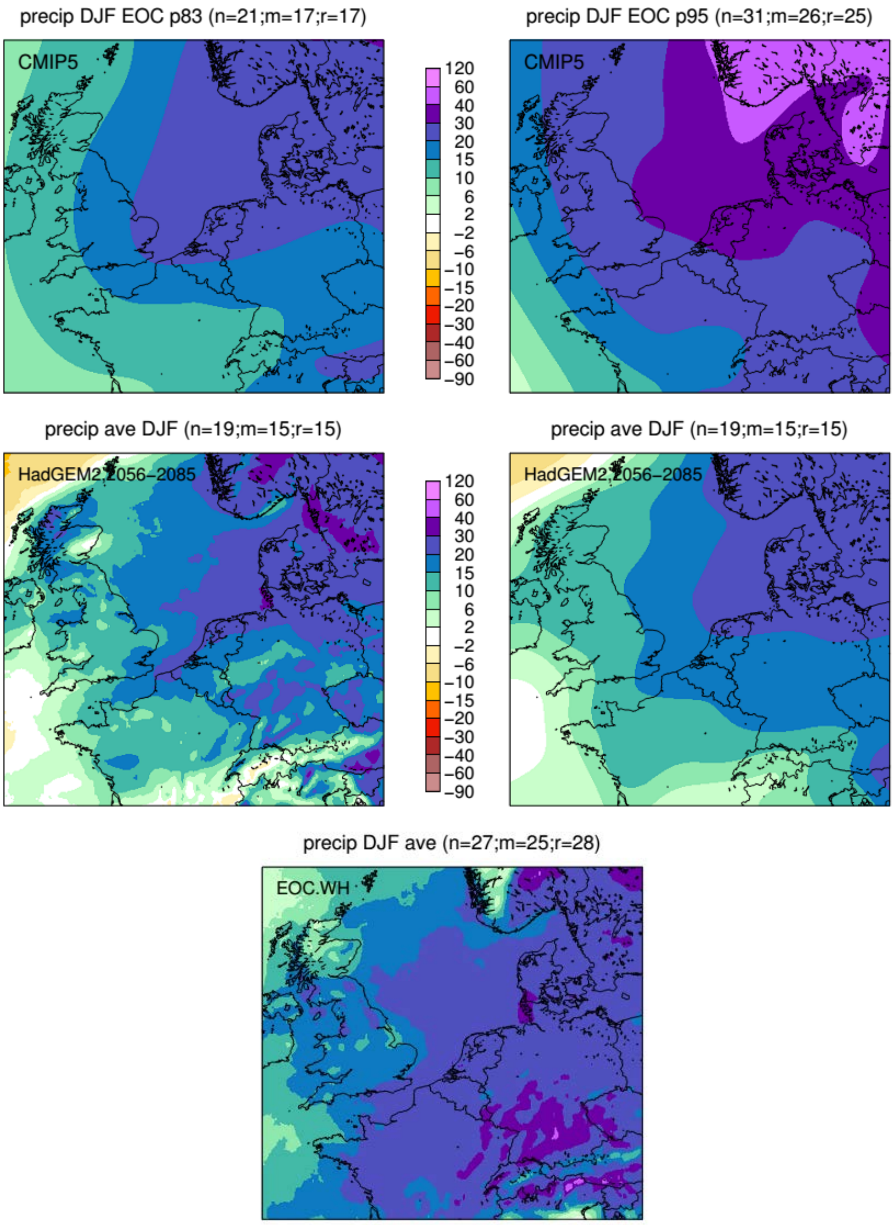

Figure 7. As Figure 2, but now for winter (DJF). For CMIP5 the 83th percentile (the median plus 1 standard deviation) and the 95th percentile are shown. Middle panels, the $W_{H,dry}$ scenario (RACMO2-HadGEM2), lower panel the W_H scenario.

For 2050 (Figure 8) the W_H scenario is within the target range given by the P83 to P95 of CMIP5 for all areas (The Netherlands, the Meuse and the Rhine catchment). The pattern of the changes over western Europe is not ideal, with too high increases over western France. The $W_{H,dry}$ scenario is again to moderate and (with the exception of the Netherlands) falls below the CMIP5 P83.

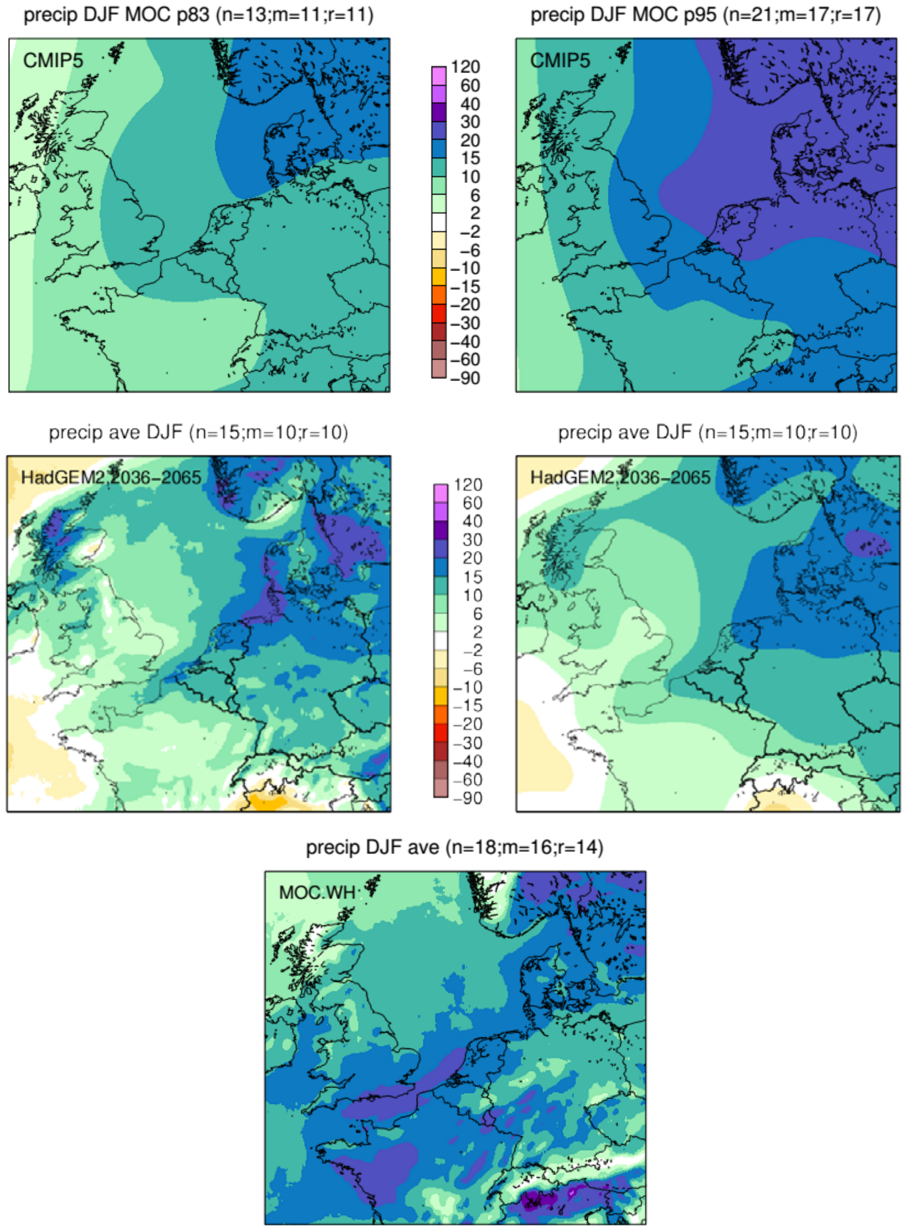

Figure 8. As Figure 2, but now for winter (DJF) in 2050. For CMIP5 the 83th percentile (the median plus 1 standard deviation) and the 95th percentile are shown. Middle panels, the $W_{H,dry}$ scenario (RACMO2-HadGEM2), lower panel the W_H scenario.

Figure 9 shows that the increase in precipitation in wet months is smaller than the mean precipitation increase. For the 90th percentile of monthly means the increase in the Rhine catchment area is 23 (13) % in the W_H ($W_{H,dry}$) scenario. In particular for the W_H scenario the increase in relatively dry months is strong. This is also a characteristic of the CMIP5 ensemble (see Figure 6 in Lenderink *et al.,* 2014). Unlike summer, the temperature increase for cold months (P10) is now strongest (see Figure 10).

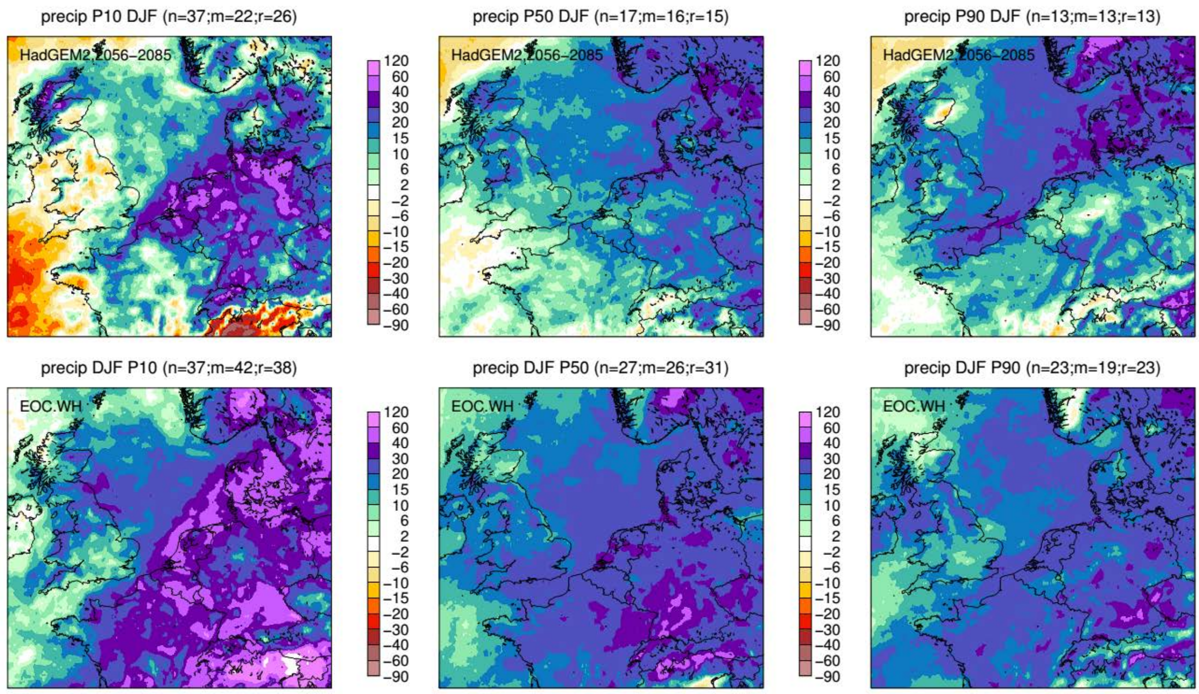

Figure 9. As Figure 5, but now for winter (DJF). Upper panels show the results for the $W_{H,dry}$ scenario (RACMO2-HadGEM2); lower panels the W_H scenario.

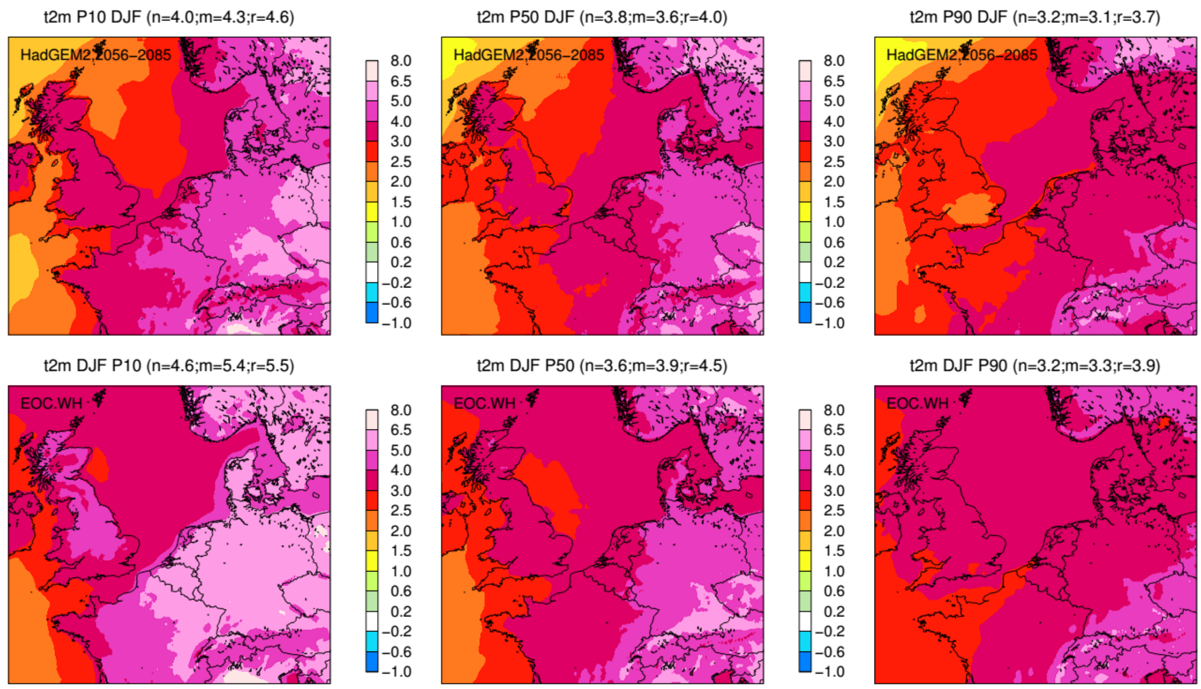

Figure 10. As Figure 6, but now for winter (DJF). Upper panels show the results for the $W_{H,dry}$ scenario (RACMO2-HadGEM2); lower panels the W_H scenario.

2.3 Seasonal cycle

The seasonal cycle of changes is shown in Figure 11. Because this figure is now derived on a monthly basis (instead of seasonal) the influence of “climate noise” is now larger, which is shown by the more noisy behaviour of the plots. The peak of drying in both scenarios is in August. A substantial decrease in precipitation is also obtained for September in the $W_{H,dry}$ scenario, apparently due to memory effects of the soil. Comparing the control periods of both scenarios to E-OBS observations it is shown that the W_H scenario has a much better control climate. The peak in precipitation in early summer is well captured in W_H (although a bit too large) but is not represented at all in $W_{H,dry}$. We note however that an error in the control climate is not necessarily linked to the validity of the climate change response, so we cannot rule out the $W_{H,dry}$ scenario based on this finding.

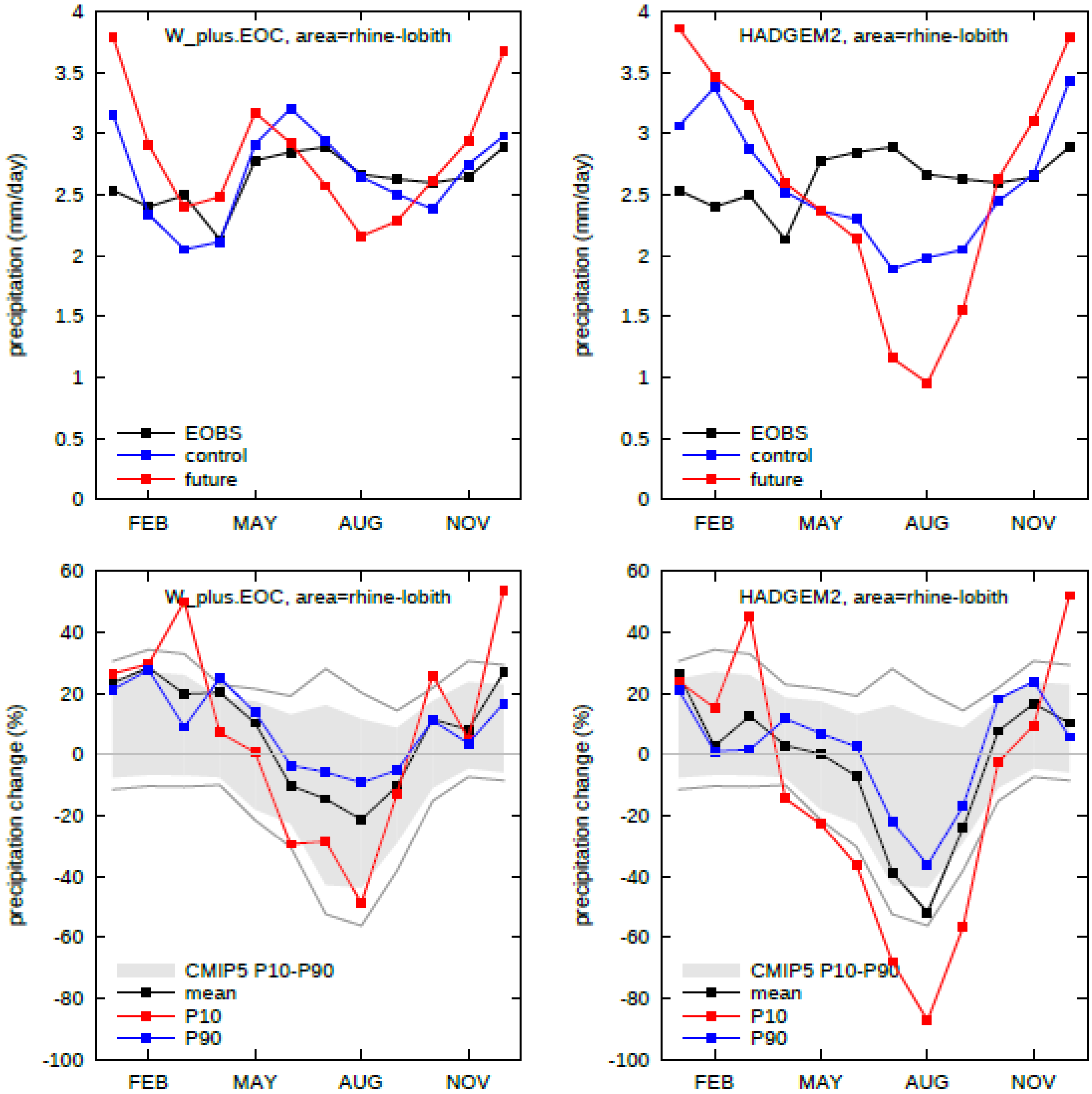

Figure 11. Upper panels: Absolute values of monthly precipitaiton, only mean over 30 years, for the control periods, the future period, and E-OBS observations. Lower panels: Percentage change (future compared to control) in monthy precipitation, mean and 10 and 90th percentile of the 30 years. Grey band: 10 to 90th percentile range of change in mean for CMIP5 simulations. Thin grey lines: CMIP5 5th and 95th percentiles (P05 and P95) of change in mean for CMIP5. Panels on the left: W_H scenario, and on the right $W_{H,dry}$ scenario for 2085.

The bottom panels show that the changes in the mean on a monthly basis for the W_H scenario (black line) lie roughly between the CMIP5 90th and 95th quantiles (grey band and grey line) in winter, and are considerably smaller than the CMIP5 5th an 10th quantiles in summer, while for the $W_{H,dry}$ scenario the changes for the winter months are clearly smaller than the CMIP5 90th and 95th quantiles, and at the same time within the CMIP5 5th an 10th quantiles in summer. With respect to the CMIP5 change ranges the W_H scenario thus best represents the scenario with large precipitation increases in winter while the $W_{H,dry}$ scenario best represents the scenario with large precipitation decreases in summer. Unfortunately for the Rhine basin (and also for the Meuse basin, but this is not shown) these two relatively extreme, but still 'likely to occur' according to the CMIP5 simulations, scenario characteristics cannot be incorporated into a single scenario like the W_H scenario does for the much smaller domain of the Netherlands alone. Further note that the $W_{H,dry}$ scenario indicates that the relative drying of the driest 10% of months in summer (red line) is much larger than the drying of average summer months.

3. Final assessment

Here, we propose $W_{H,dry}$ as a new scenario for 2050 and 2085, in addition to the four existing scenarios. This new scenario is specifically targeted at representing severe drought conditions in summer, in particular for the Rhine catchments area – conditions that occur in a limited number (10 to 20%) of the CMIP5 model simulations. The new scenario is derived from a downscaling with the KNMI regional climate model RACMO of the global climate model HadGEM2-ES.

In comparison with the CMIP5 models the new $W_{H,dry}$ scenario for 2085 has the right amount of drying (approaching the 5-15 % most extreme CMIP5 simulations) for JJA for both the Rhine and the Meuse catchment (see tables in Appendix A) and is consistent with a value of the global temperature rise of 3.5 °C. We note this scenarios is slightly more extreme than is apparent from the analysis for JJA as the drying also extends into September (see Figure 11 and Appendix B). For 2050, we did not take the time periods with a global warming of 2 °C – the target steering variable for the W scenarios – but took a 5 year later period with a global temperature of 2.3 °C. This is necessary in order to achieve a sufficient decrease in summer precipitation. The downside, however, is that the temperature change is slightly (0.2 to 0.4 °C) too high for the Rhine and Meuse catchments.

Given all the information provided above, and the tables provided in Appendix A, we propose to retain W_H as a wet scenario, also for the Rhine catchment area. The major drawback of this scenario is that the increase in winter mean (+28%) precipitation is 3% above the target value of 25% as set by the 95th percentile of the CMIP5 outcomes for winter mean precipitation change. This is admittedly slightly high, however the difference is well within the margins set by the uncertainty due to natural variability; for instance, in the 16 member ensemble the standard deviation in the Rhine mean precipitation response – entirely related to natural variability – is already 5 %. Also, note that the change in relatively dry months has a relatively large contribution to the mean change. The change in wet winter months, represented by the 90th percentile of monthly mean precipitation which is more relevant for flooding, is smaller (+23%) (see Figure 9, lower right panel). This change is well within the range provided by the RACMO2 ensemble: from the 16 members of this ensemble 3 members have an increase larger or equal 23% for this statistic. We therefore conclude that for the Rhine basin W_H is a plausible scenario representing the upper CMIP5 range (between P95 and P97.5).

References

Christensen, J.H., E. Kjellström, F. Giorgi, G. Lenderink and M. Rummukainen, 2010. Assigning relative weights to regional climate models: Exploring the concept. *Climate Research*, **44**, 179-194, doi:10.3354/cr00916.

Haarsma, R.J., F.M. Selten, B.J.J.M. van den Hurk, W. Hazeleger and X. Wang, 2009. Drier Mediterranean Soils due to Greenhouse Warming bring easterly Winds over Summertime Central Europe. *Geophys. Res. Lett.*, **36**, L04705, doi:10.1029/2008GL036617.

Hurk, B. van den, P. Siegmund, A. Klein Tank (Eds), J. Attema, A. Bakker, J. Beersma, J. Bessembinder, R. Boers, T. Brandsma, H. van den Brink, S. Drijfhout, H. Eskes, R. Haarsma, W. Hazeleger, R. Jilderda, C. Katsman, G. Lenderink, J. Loriaux, E. van Meijgaard, T. van Noije, G.-J. van Oldenborgh, F. Selten, P. Siebesma, A. Sterl, H. de Vries, M. van Weele and R. de Winter en G.-J. van Zadelhoff, 2014. KNMI'14: Climate Change scenarios for the 21st Century - A Netherlands perspective. KNMI publication: WR-2014-01, KNMI, De Bilt, The Netherlands, pp120.

KNMI, 2015 (Klein Tank, A., J. Beersma, J. Bessembinder, B. van den Hurk and G. Lenderink). KNMI’14 climate scenarios for the Netherlands; A guide for professionals in climate adaptation (Revised edition 2015), KNMI, De Bilt, The Netherlands, 34pp.

Lenderink, G., A. van Ulden, B. van den Hurk and F. Keller, 2007. A study on combining global and regional climate model results for generating climate scenarios of temperature and precipitation for the Netherlands. *Clim. Dyn.*, **29**, 2, 157-176, doi:10.1007/s00382-007-0227-z.

Lenderink, G., B.J.J.M. van den Hurk, A.M.G. Klein Tank, G.J. van Oldenborgh, E. van Meijgaard, H. de Vries and J.J. Beersma, 2014. Preparing local climate change scenarios for the Netherlands using resampling of climate model output. *Environmental Research Letters*, **9**, 11, 115008, doi:10.1088/1748-9326/9/11/115008.

Selten, F.M., R. Bintanja, R. Vautard and B.J.J.M. van der Hurk. Future continental summer warming constrained by the present-day seasonal cycle of surface hydrology. Manuscript in preparation.

Appendix A: CMIP5 percentiles and KNMI'14 scenarios

In this appendix we show seasonal changes in precipitation and temperature averaged over the three areas (the Netherlands, the Meuse catchment and the Rhine catchment) for each of the five KNMI'14 scenarios for 2085 and 2050 in comparison with the corresponding percentile changes (P05 to P95) obtained from the CMIP5 projections considered for KNMI'14.

Precipitation change (%) 2085							
CMIP5 percentilel KNMI'14 scenario	DJF NL	DJF Meuse	DJF Rhine	*CMIP5 percentilel* KNMI'14 scenario	JJA NL	JJA Meuse	JJA Rhine
P05	**-4**	**-5**	**-5**	*P05*	*-37*	*-42*	*-40*
P10	**-1**	**-2**	**-2**	***P10***	**-31**	**-36**	**-34**
P17	**1**	**0**	**0**	$W_{H,dry}$	-24*	-33	-31
P25	*3*	*2*	*2*	***P17***	**-26**	**-30**	**-28**
G_L	4.5	5	7	W_H	-23	-25	-15
P50	*10*	*8*	*8*	*P25*	*-21*	*-23*	*-20*
G_H	12	10	9	*P50*	*-9*	*-11*	*-7*
W_L	13	13	17	W_L	-5	-14	-6
P75	*18*	*15*	*14*	G_H	-8	-8	-5
$W_{H,dry}$	19*	15	15	*P75*	*2*	*-1*	*1*
P83	**21**	**17**	**17**	G_L	1	-1	2
P90	**25**	**20**	**19**	***P83***	**7**	**3**	**5**
W_H	30	25	28	***P90***	**12**	**8**	**10**
P95	**31**	**26**	**25**	***P95***	**24**	**19**	**18**
P97.5	*36*	*29*	*29*				

Table 1. Relative changes in precipitation in CMIP5 percentiles (P05 to P95) and the five KNMI'14 scenarios in 2085 with respect to the reference period (1981-2010) for the Netherlands (NL), the Rhine and the Meuse in winter and summer. The target CMIP5 ranges for the "upper" and "lower" KNMI'14 scenarios are shown as bold figures(see also paragraph 5 on page 6). For the KNMI'14 scenarios red figures means the "upper" (or "lower") scenario of the set is "too dry" according to the CMIP5 range, blue figures means it is "too wet". Scenarios W_H and (the new) $W_{H,dry}$ are "twin-scenarios" applicable to the Meuse and Rhine basins only. The coloured background only applies to these twin-scenarios; green denotes the relevant "upper" scenario for either winter or summer, orange means a relevant scenario but not representing the upper range from CMIP5 (i.e. the scenario underestimates either the largest 'likely' precipitation increase in winter or the largest 'likely' precipitation decrease in summer).
* Note that $W_{H,dry}$ is not one of the four official KNMI'14 scenarios for the Netherlands (KNMI, 2015).

Temperature change (°C) 2085							
CMIP5 percentile/ KNMI'14 scenario	NL	DJF Meuse	Rhine	*CMIP5 percentile/ KNMI'14 scenario*	NL	JJA Meuse	Rhine
P05	***1.0***	***1.0***	***1.1***	***P05***	***0.8***	***1.0***	***1.1***
P10	***1.2***	***1.2***	***1.3***	**G_L**	1.2	1.3	1.4
G_L	1.3	1.4	1.6	***P10***	***1.4***	***1.6***	***1.7***
P17	***1.4***	***1.5***	***1.6***	**G_H**	**1.7**	**1.9**	**2.0**
P25	*1.6*	*1.7*	*1.8*	***P17***	***1.7***	***2.0***	***2.1***
G_H	**2.0**	**2.0**	**2.2**	*P25*	*2.0*	*2.3*	*2.5*
P50	*2.4*	*2.4*	*2.7*	*P50*	*2.6*	*3.0*	*3.1*
P75	*3.1*	*3.2*	*3.5*	**W_L**	**3.2**	**3.7**	**3.9**
W_L	**3.2**	**3.5**	**3.9**	*P75*	*3.7*	*4.2*	*4.4*
P83	***3.6***	***3.5***	***3.8***	**W_H**	3.7	4.4	4.4
$W_{H,dry}$	3.7*	3.6	4	***P83***	***4.2***	***4.9***	***5.1***
W_H	4.1	4.1	4.6	**$W_{H,dry}$**	4.4*	5.5	5.9
P90	***4.1***	***4.2***	***4.5***	***P90***	***4.9***	***5.6***	***5.8***
P95	***4.8***	***4.8***	***5.2***	***P95***	***5.8***	***7.0***	***7.5***

Table 2. As Table 1, but now for the temperature change in 2085 compared to the reference period (1981-2010). For the KNMI'14 scenarios red figures means the "upper" (or "lower") scenario of the set is "too warm" according to the CMIP5 range, blue figures means it is "too cold".
*** Note that $W_{H,dry}$ is not one of the four official KNMI'14 scenarios for the Netherlands (KNMI, 2015).**

Precipitation change (%) 2050							
CMIP5 percentile/ KNMI'14 scenario	NL	DJF Meuse	Rhine	*CMIP5 percentile/* KNMI'14 scenario	NL	JJA Meuse	Rhine
P05	***-5***	***-6***	***-6***	*P05*	*-25*	*-28*	*-26*
P10	***-2***	***-3***	***-3***	***P10***	***-21***	***-23***	***-20***
P17	***0***	***-1***	***-1***	**$W_{H,dry}$**	**-15***	**-20**	**-17**
P25	*1*	*1*	*1*	***P17***	***-17***	***-18***	***-15***
G_L	**3**	**3**	**3**	*P25*	*-13*	*-14*	*-10*
P50	*6*	*5*	*5*	**W_H**	**-13**	**-13**	**-8**
G_H	**8**	**6**	**5**	**G_H**	**-8**	**-8**	**-3**
W_L	**8**	**6**	**8**	*P50*	*-4*	*-5*	*-3*
P75	*11*	*9*	*9*	**W_L**	**1.4**	**-3**	**-1**
$W_{H,dry}$	**15***	**10**	**10**	**G_L**	**1.2**	**0**	**0**
P83	***13***	***11***	***11***	*P75*	*4*	*2*	*3*
P90	***16***	***13***	***13***	***P83***	***7***	***5***	***6***
W_H	**17**	**16**	**14**	***P90***	***12***	***10***	***10***
P95	***21***	***17***	***17***	***P95***	***20***	***16***	***15***

Table 3. As Table 1, but now for the precipitation change in 2050 compared to the reference period (1981-2010). For the KNMI'14 scenarios red figures means the "upper" (or "lower") scenario of the set is "too dry" according to the CMIP5 range, blue figures means it is "too wet".

*** Note that $W_{H,dry}$ is not one of the four official KNMI'14 scenarios for the Netherlands (KNMI, 2015).**

Temperature change (°C) 2050							
CMIP5 percentile/ KNMI'14 scenario	NL	DJF Meuse	Rhine	*CMIP5 percentile/* KNMI14 scenario	NL	JJA Meuse	Rhine
P05	***0.5***	***0.6***	***0.7***	***P05***	***0.6***	***0.8***	***0.8***
P10	***0.7***	***0.8***	***0.9***	***P10***	***0.9***	***1.0***	***1.1***
P17	***0.9***	***0.9***	***1.0***	**G_L**	**1.0**	**1.1**	**1.1**
P25	*1.0*	*1.1*	*1.2*	***P17***	***1.0***	***1.2***	***1.3***
G_L	**1.1**	**1.2**	**1.3**	*P25*	*1.2*	*1.5*	*1.5*
P50	*1.5*	*1.5*	*1.6*	**G_H**	**1.4**	**1.5**	**1.5**
G_H	**1.6**	**1.7**	**1.8**	*P50*	*1.7*	*1.9*	*2.0*
P75	*2.0*	*2.0*	*2.2*	**W_L**	**1.7**	**2.0**	**2.2**
W_L	**2.1**	**2.2**	**2.5**	*P75*	*2.3*	*2.5*	*2.5*
P83	***2.2***	***2.2***	***2.4***	**W_H**	**2.3**	**2.6**	**2.7**
P90	***2.5***	***2.4***	***2.6***	***P83***	***2.6***	***2.9***	***2.9***
$W_{H,dry}$	**2.7***	**2.5**	**2.9**	***P90***	***2.9***	***3.3***	***3.4***
W_H	**2.7**	**2.7**	**3.0**	**$W_{H,dry}$**	**2.8***	**3.5**	**3.8**
P95	***2.8***	***2.8***	***3.0***	***P95***	***3.3***	***3.8***	***3.9***

Table 4. As Table 1, but now for the temperature change in 2050 compared to the reference period (1981-2010). For the KNMI'14 scenarios red figures means the "upper" (or "lower") scenario of the set is "too warm" according to the CMIP5 range, blue figures means it is "too cold".

*** Note that $W_{H,dry}$ is not one of the four official KNMI'14 scenarios for the Netherlands (KNMI, 2015).**

Appendix B: Supplementary model results and evaluation

Here, we show a short evaluation of the simulations with RACMO2 with E-OBS observations. To evaluate the quality of RACMO2 (as a downscaling tool) we compare a run driven by reanalysis boundaries from ERA-interim to E-OBS. We also evaluate the ensemble of 16 model simulations with RACMO driven by EC-Earth. The first 8 of these simulation form the basis of the KNMI'14 scenarios.

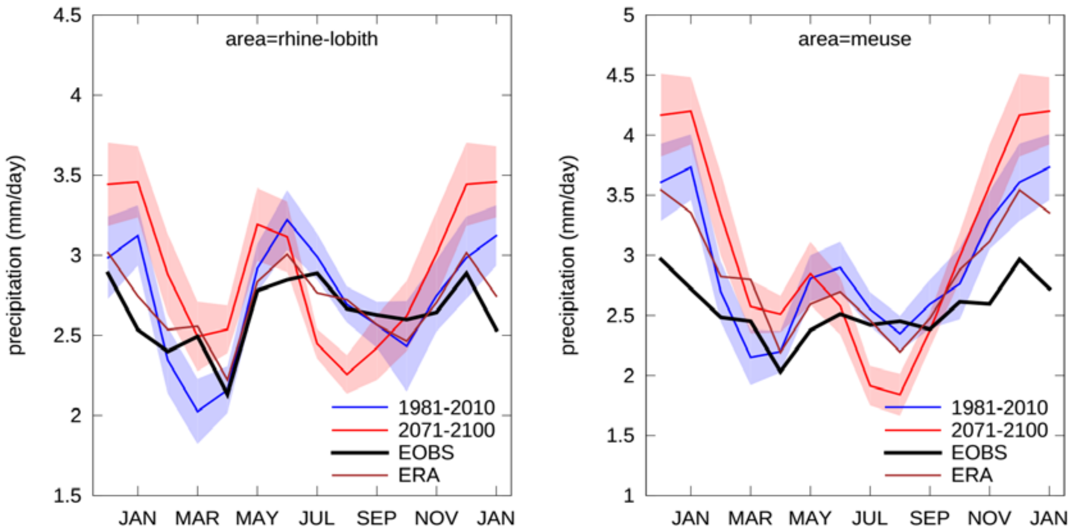

Figure 12. Seasonal cycle Rhine catchment in EOBS, RACMO2 driven by ERA-interim (ERA) (both period 1981-2010), the mean of control simulation of the 16 members ensemble EC-Earth-RACMO2, and the future period 2071-2100. The ensemble mean results are shown by thick lines, whereas the spread within the ensemble (standard deviation) is shown by the colored bands.

For the Rhine catchment area the ERA-interim run is very close to E-OBS, with differences in the monthly means over the 30 years period of typically 0.1-0.2 mm/day (less than 10% of the means) (Figure 12). In addition, the time series of the monthly means correlate very well with the E-OBS time series, varying from 0.99 in winter and 0.91 in summer. In winter, the distribution of monthly means over the catchment area is also very good, both for the wet extremes as well as for the dry extremes (Figure 13). For summer, the wet extremes are good, but the model overestimates precipitation amounts for very dry months (see right bottom panel of Figure 13). For the Meuse catchment (which is much smaller in spatial extend) the seasonal cycle is also reasonably well captured, but the model over-predicts precipitation in winter by 20%. In general, these figures show a very good agreement with the RACMO2 reanalysis run with the observations (often within the error in the observational data).

The results for the control period of the ensemble of RACMO2 are generally close to the reanalysis run, thus showing the quality of EC-Earth as a driving GCM.

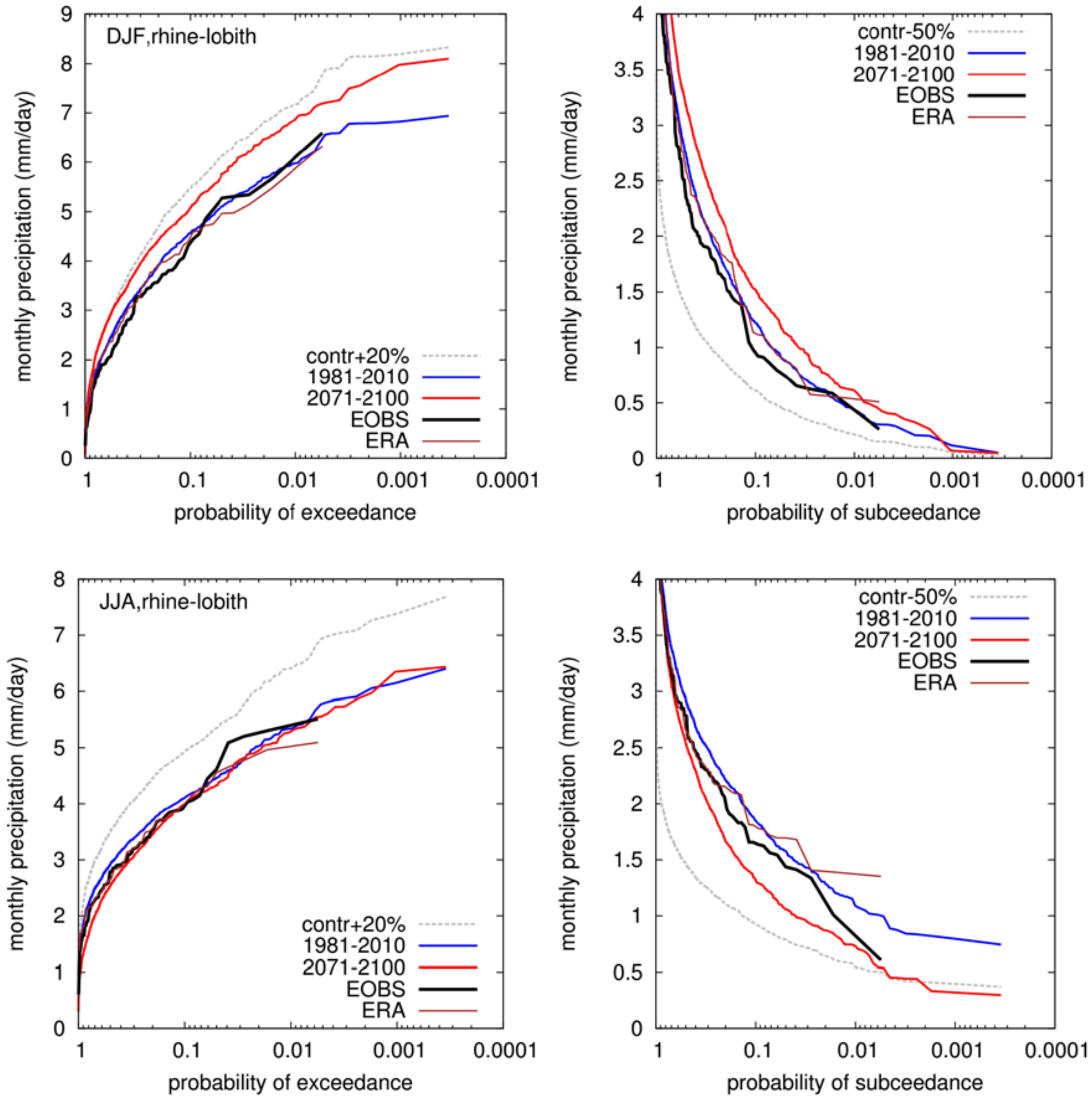

Figure 13. Probability of exceedance (wet extremes) and subceedance (dry extremes) for winter (DJF) and summer (JJA) for the Rhine catchment area. Lines and colors similar to the previous figure. As a guide to the eye we also plotted an intensity increase of +20 % for the wet extremes in the panels on the left-hand side and -50 % for the dry extremes on the right-hand side.

The mean change in winter precipitation in the model ensemble reveals a moderately strong increase of 18 % at the end of this century (2071-2010). Although the period is five years later than the period used for the resampling of data for the scenarios, it is not unreasonably to compare these results to the W_H and W_L scenarios. The pattern of the changes is similar to the W_H scenario with a relatively strong increase for central Europe, just north of the Alps. Again for the wet months the increase is somewhat smaller than the change for the seasonal mean, 15 % versus 18% respectively for the Rhine basin. That the climate is very variable in winter is illustrated by the panels in Figure 14 and Figure 15, where the individual results of the first 8 members are shown.

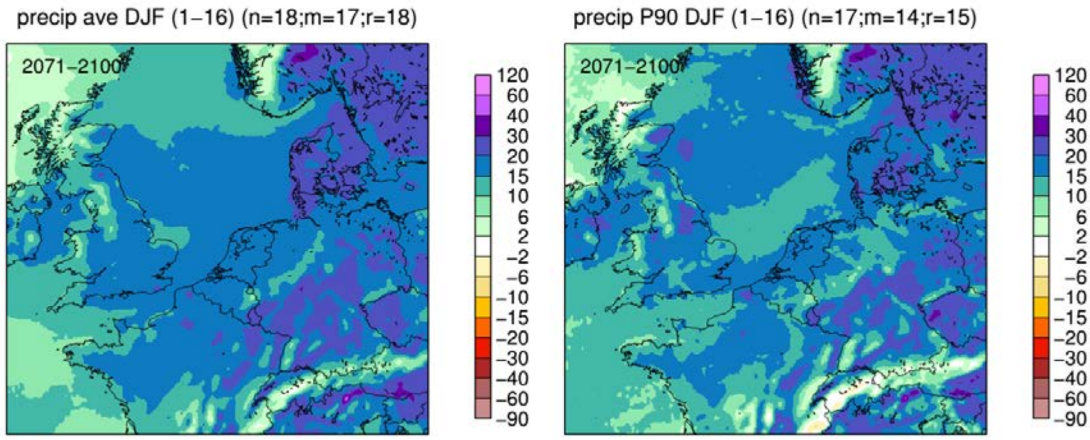

Figure 14. Mean response over 16 members of RACMO2/EC-Earth for mean winter precipitation (left) and P90 of monthly winter precipitation (right). Percentage differences between the control period 1981-2010 and the future period 2071-2100 are shown.

In particular in winter the climate is variable, with typical variations in the response at a local level of 10 % to 15%, which is approximately the same order as the average climate change response.

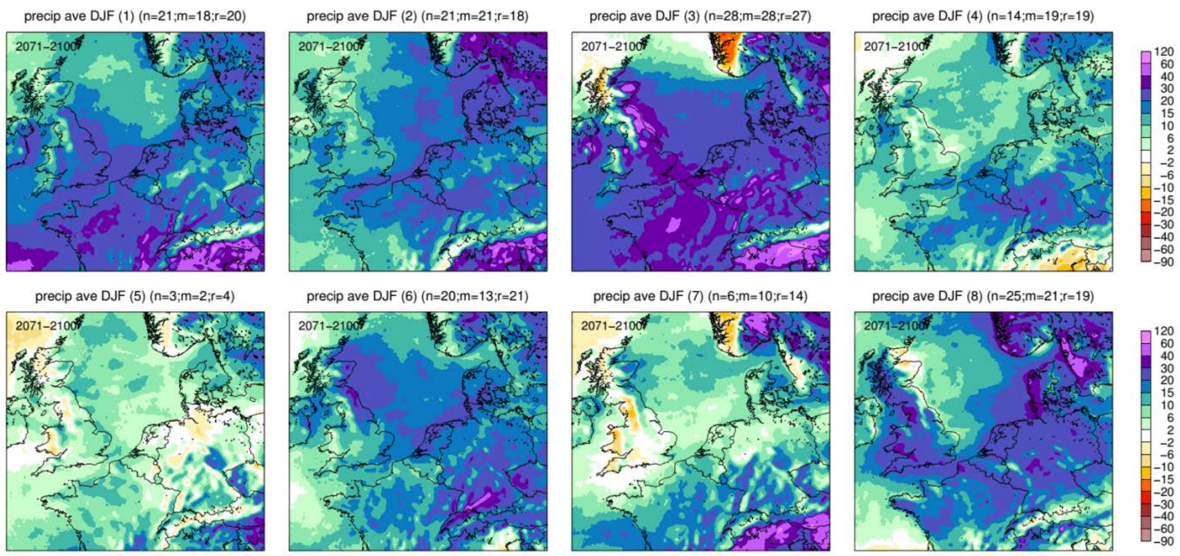

Figure 15. Panel of changes in seasonal mean precipitation in winter (DJF) comparing 2071-2010 with 1981-2010 derived from the first 8 members of the RACMO2 ensemble (driven by EC-Earth).

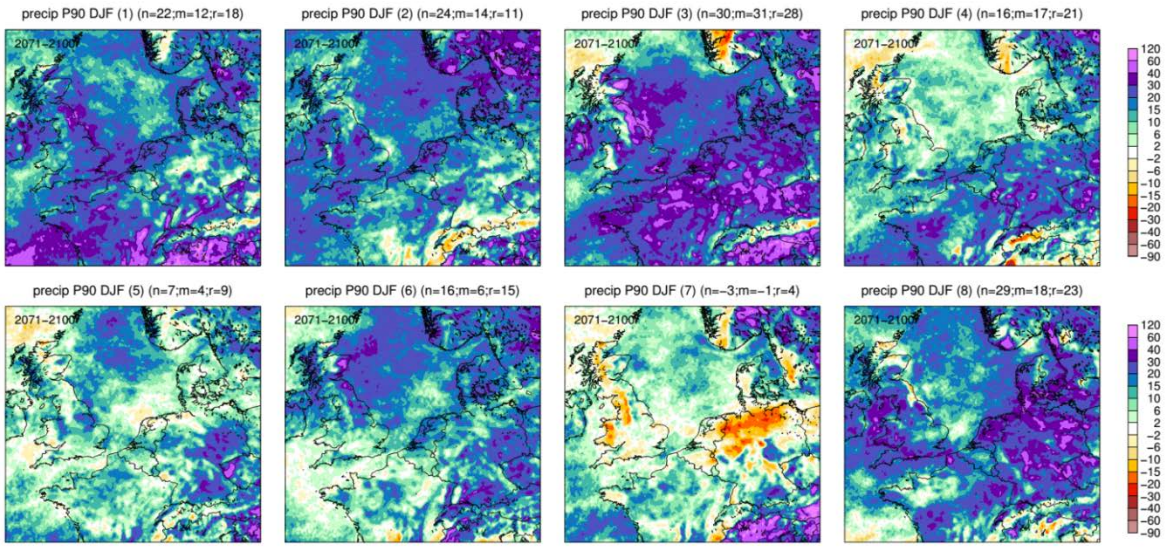

Figure 16. As Figure 15, but now for changes in the wet months (P90 of the distribution of monthly precipitation).