CORDEX.be II: Scenarios & Global Climate Model Selection

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An overview of the CORDEX.be II proposed climate scenarios, future periods and selection of global climate models (GCMs) for the CORDEX.be II simulations. This report describes these choices and the methodology used to select the GCMs, future periods and scenarios.

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1 Introduction

The main aim of CORDEX.be II is to close the gap between regional climate model information and local impacts in order to provide climate services to support climate adaptation and mitigation. To achieve this ambition the project will simulate future climates in different scenarios and translate this information into local impacts. The local climate can be simulated using regional climate models (RCMs). Regional climate models downscale ("zoom in on") global climate model (GCMs) on a smaller domain (e.g. Belgium). RCMs increase the resolution of the climate simulations which results in a more detailed representation of the climate, see Figure 1.

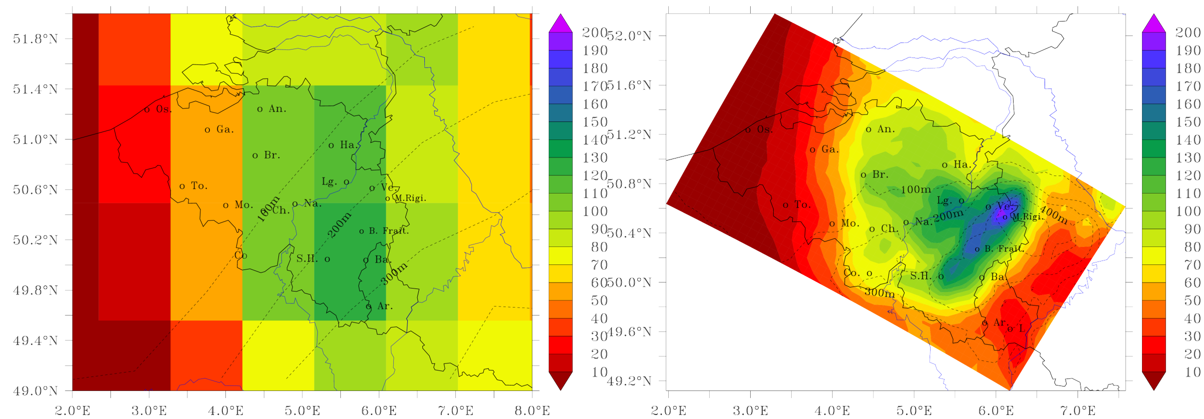
The 6^{th} IPCC assessment report (AR6) makes use of 60 different GCMs from the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) and 24 RCMs from the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Gutiérrez & Treguier, 2021). Due to their higher resolution, RCMs better represent extreme precipitation events at sub-daily time scales (Prein et al., 2015; Termonia, Van Schaeybroeck, et al., 2018) and are therefore well suited to study extreme events which are expected to increase in intensity and frequency in the future (Masson-Delmotte et al., 2021). In the CORDEX.be II project we will use 3 RCMs at 4km resolution over Belgium: ALARO, COSMO-CLM and MAR, and each RCM will downscale (zoom) multiple GCMs.

All three RCMs were used in the first CORDEX.be project and have been improved since then. MAR (Modèle Atmosphérique Régional) (Wyard et al., 2017) is a hydrostatic RCM developed by the Liège University. The latest version of MAR (v3.14) includes a new convection scheme (Doutreloup et al., 2019), parametrization of the urban heat island, and improved simulation of energy fluxes and vegetation seasonality. COSMO-CLM is a non-hydrostatic RCM that is maintained by the Climate Limited-area Modeling (CLM) community. This community continuously improves the model and the latest version (COSMO-CLM 6.0), which uses the TERRA-URB (Trusilova et al., 2015) land-surface scheme, will be used in the CORDEX.be II project. Finally, ALARO is an RCM developed by the international ALADIN consortium (Termonia, Fischer, et al., 2018). The latest version (ALARO-1) will be used together with a surface scheme SURFEX (Hamdi et al., 2014; Masson et al., 2013) which better simulates urban areas.

High-resolution RCM-simulations are computationally expensive and therefore, combining all RCMs and GCMs is not feasible. Additionally, the computational cost also limits the number of future time periods one can reasonably simulate. Therefore, within CORDEX.be II, we are forced to select 7 GCMs that will each by downscaled by at least one of the 3 RCMs for the current climate and two 20-year future periods.

RCM-simulations are not only computationally expensive, they are also time consuming to run. Once these simulations have started, decisions on the scenarios and the selected GCMs to downscale (zoom) can not be changed. Therefore, it is important that the chosen scenarios and selected GCMs are in line with the project goals and the stakeholders needs. This report describes these choices using scientific arguments and stakeholder priorities.

In a later stage, the CORDEX.be II project will help translate these RCM simulations to local impacts. This will be done by using the RCM simulations as input for impact models. Two hydrological impact models (SCHEME and WOLF) will be used to simulate flooding in river basins. The urban model URBCLIM will make 100m resolution simulation that can be used alongside the urban observation campaign to evaluate the micro-scale (e.g. buildings and trees) impact of cities on the local climate. Major Belgian cities will also be simulated at a 1km resolution using the urban model SURFEX. Additionally, the project aims to co-create "tales of future weather" together with core stakeholders which will enable stakeholder-relevant climate impacts to be investigated.



(a) The output of a global climate model (GCM) over Belgium

(b) The output of the MAR regional climate model (RCM) which downscaled (zoomed) the GCM over Belgium

Figure 1: An illustration of the difference in resolution between a GCM and a RCM for an extreme rain event (mm over 3 days). The GCM output is at a 100km by 100km resolution and the RCM output is at a 4km by 4km resolution.

2 Stakeholders

CORDEX.be II is a stakeholder-driven project that aims to co-create actionable climate information. The 6 core stakeholders have different interests (e.g. water, cities and critical infrastructure) and will therefore use the anticipated climate data differently. The main focus of this core stakeholder group is to use state-of-the-art climate information to support climate adaptation. Through multiple interactions with the core group, the CORDEX.be II project has identified the following key priorities:

1) The need for wide range of detailed climate parameters at high spatial and temporal resolution.
2) The need for climate information that covers the worst-case scenarios but are still plausible, especially for those interested in climate adaptation.
3) The need for easy access to the project outputs, including better access to the previous CORDEX.be I simulations.[1]
4) The interest in a one clear message on the future climate in Belgium.
5) The interest of some stakeholders in co-creating "tales of future weather".
6) The need for clear communication regarding the methodology, in particular the differences between CORDEX.be I and CORDEX.be II.

These priorities are taken into account in every decision made in the CORDEX.be II project.

! CORDEX.be II Stakeholders

The CORDEX.be II stakeholders are an integral part of this project.

3 Climate Scenarios and Global Warming Levels

There are many different sources of uncertainty in climate projections. One of the main sources of uncertainty is the future greenhouse gas emissions. To include this uncertainty in climate projections a set of climate scenarios called the Socio-economic Shared Pathways (SSPs) have been developed. The SSPs describe different possible paths that the world could take based on different socio-economic developments. The SSP scenarios were used in the latest (6^{th}) IPCC Assessment Report and replace the older representative concentration pathways (RCPs) that were used in the 5^{th} IPCC Assessment Report and CORDEX.be I project.

[1] In May 2024, the Belgian Climate Center will present the CORDEX.be I simulations and how they can be easily accessed through the federal geospatial portal Geo.be.

3.1 What are global warming levels?

Global warming levels (GWL) are time periods that describe what our future climate will be in case the global temperature reaches a certain level. This enables the exploration of the climate in, for example, a +2°C warmer world which are directly linked to the policy ambitions of the Paris Agreement. Figure 2 illustrates the global warming level framework showing the average increase in temperature of the hottest day per GWL. This framework can inform what adaptations might be required at each level of global warming and, in doing so provide extra incentives for avoiding higher GWLs.

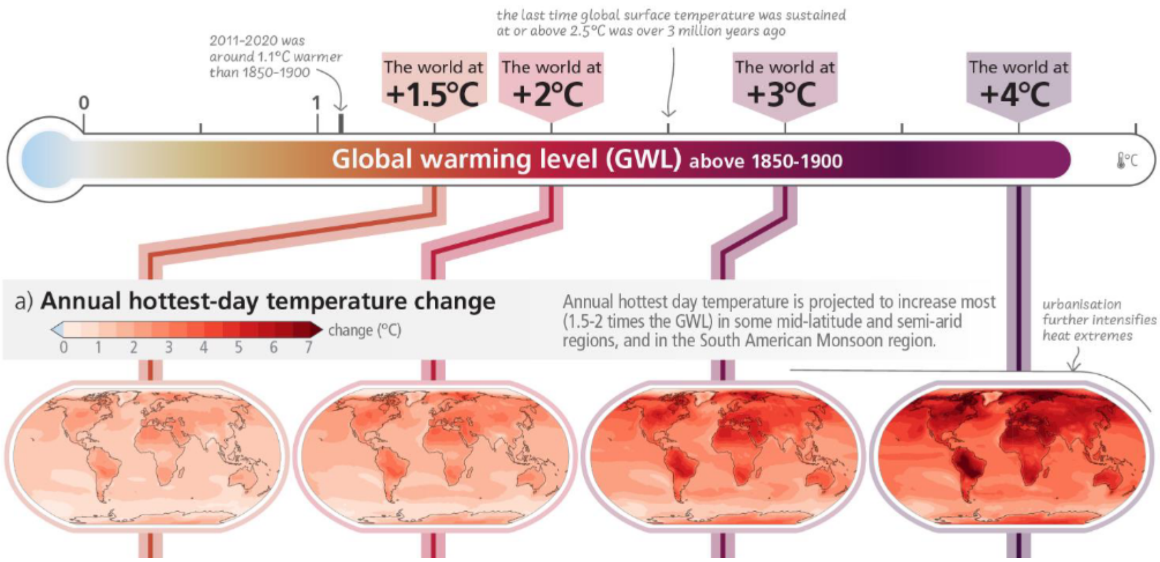


Figure 2: Illustration of the global warming level framework. From (Masson-Delmotte et al., 2021).

The different SSP scenarios can be viewed as routes that pass different GWLs at different time periods. As illustrated in Figure 3, the most extreme scenarios (SSP5-8.5) reaches the +2°C GWL the fastest and it reaches GWLs that other scenarios do not.

Using the global warming level framework assumes that a GWL is independent of the SSP scenario. For example, a combination of SSP scenarios is considered together to create one picture of the future climate at a +2°C GWL. In this framework, the scenarios are only informative for *when* we could expect to reach a +2°C warmer world.

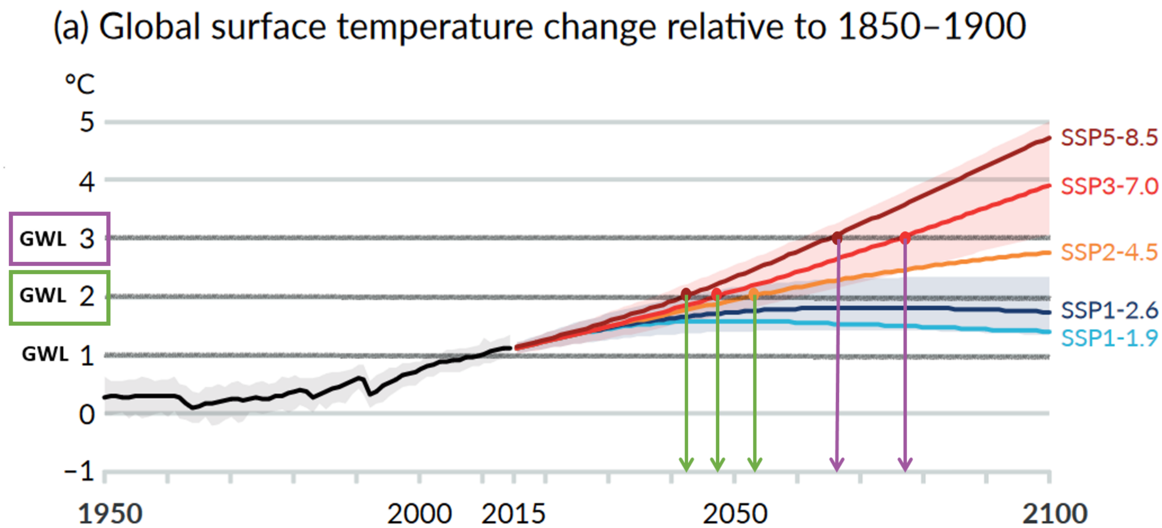


Figure 3: Illustration of the Socio-economic pathways (SSPs) and the different timing in which they reach GWL +2°C and GWL +3°C. Adapted from (Masson-Delmotte et al., 2021).

3.2 What is the current global warming level?

A global warming level is the average global temperature increase relative to pre-industrial levels[2]. A global warming level represents an increase in *global average* temperature. The average temperature is taken over a long period of time (minimum of 10 years) to avoid the influence of natural variability. In this project 20-year average temperature will be used.

The average temperature increase over Belgium and Europe so far exceeds the global average warming and will very likely continue to do so in the future. The current warming trend in Belgium and Europe is approximately twice as fast as the global average warming ("WMO's state of the climate in europe report for 2022 | world meteorological organization," 2022). This implies that a 2°C warmer world (GWL) is equivalent to a 4°C warmer Belgium.

Current Global Warming Level

The current global warming level is between +1.1°C and +1.3°C.

The current global warming level is estimated by comparing the average temperature in the recent past (at least 10 years) to the pre-industrial (1850-1900) average temperature. In Table 1, an overview of the current global warming level estimates is provided. The main difference

[2]For a more rigorous discription see the GCM selection technical report

between the estimates is the period considered. The Copernicus climate tracker and Climate action tracker are updated on a monthly basis.

Source	Current GWL estimate	Period considered	Date of estimate	Reference
6^{th} IPPC assessment report	+1.09°C[3]	[2011-2020]	March 2023	(Lee et al., 2023)
Scientific Article	+1.15°C[4]	[2013-2022]	May 2023	(Forster et al., 2023)
Copernicus climate tracker	+1.25°C	[Dec 1993 - Dec 2023]	January 2024	Copernicus climate tracker
Climate action tracker	+1.3°C	-	December 2023	Climate action tracker see Figure 5

Table 1: An overview of the current global warming level estimates. The average temperature in the considered period is compared to the pre-industrial level.

The CORDEX.be II simulations will explore the future local climate in Belgium for two different GWLs: +2°C and +3°C (global) warmer world and compare these to the recent past (1995-2014).

3.3 Why +2°C and +3°C GWLs?

Ideally, simulating all GWLs would be the best option. However, this is not feasible due to the large computational cost of RCM simulations. Therefore, two GWLs will be simulated in the CORDEX.be II project. The selection of these two GWLs is guided by the stakeholders' need for climate information that covers the worst-case scenarios that are still plausible assuming the realization of the current international climate pledges. An investigation of the current-day GWL and the expected timing of the different GWLs is required.

To get an idea of when or if a GWL will be reached, we can look at the SSP scenarios that describe several possible futures, including but not limited to the evolution of future greenhouse gas emissions. By following one of these scenarios from their origin in 2015 to 2100 one can clearly see if and when each GWL is reached. In 2023, 8 years into these scenarios, the global carbon project (Friedlingstein et al., 2023) derived the actual greenhouse gas emissions up to 2022, see Figure 4. If current climate pledges are met, the SSP1-2.6 and SSP2-4.5 scenarios best fit the expected emissions this century and the corresponding peak GWLs are 1.8°C and 2.7°C respectively.

[3]range: [+0.95°C, +1.20°C]
[4]range: [+1°C, +1.25°C]

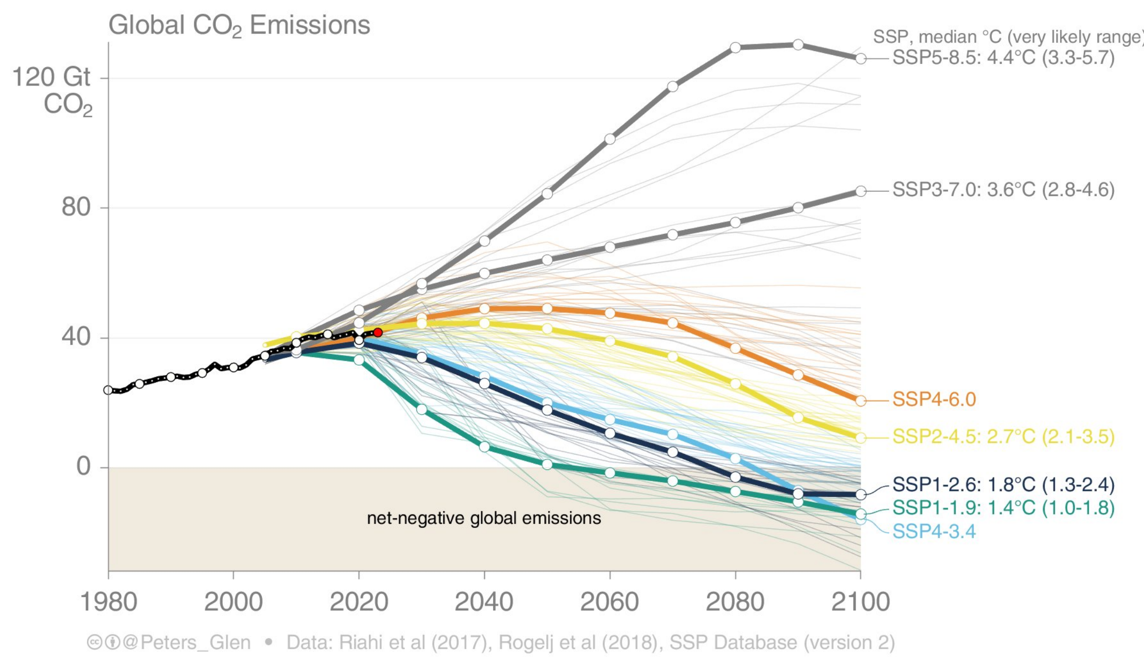


Figure 4: The total global greenhouse gas emissions per year. Black line - The historical emission estimated by the global carbon project (Friedlingstein et al., 2023). Colored lines - The emissions pathway per SSP scenario (Riahi et al., 2017; Rogelj et al., 2018). For the most used scenarios, the estimated global warming by 2100 is provided.

The United Nations Emission Gap Report 2023 (*Emissions Gap Report 2023*, 2023) corroborates this observation, estimating a peak warming between 2.5°C[5] and 3°C[6] in this century. Similar findings are nicely illustrated by the Climate action tracker see Figure 5. In addition, there is a wide scientific consensus that the most extreme GWL +4°C and corresponding scenario SSP 5-8.5 should no longer be considered plausible (Hausfather & Peters, 2020; "Mitigation pathways compatible with long-term goals," 2023 pg 386; Scafetta, 2024).

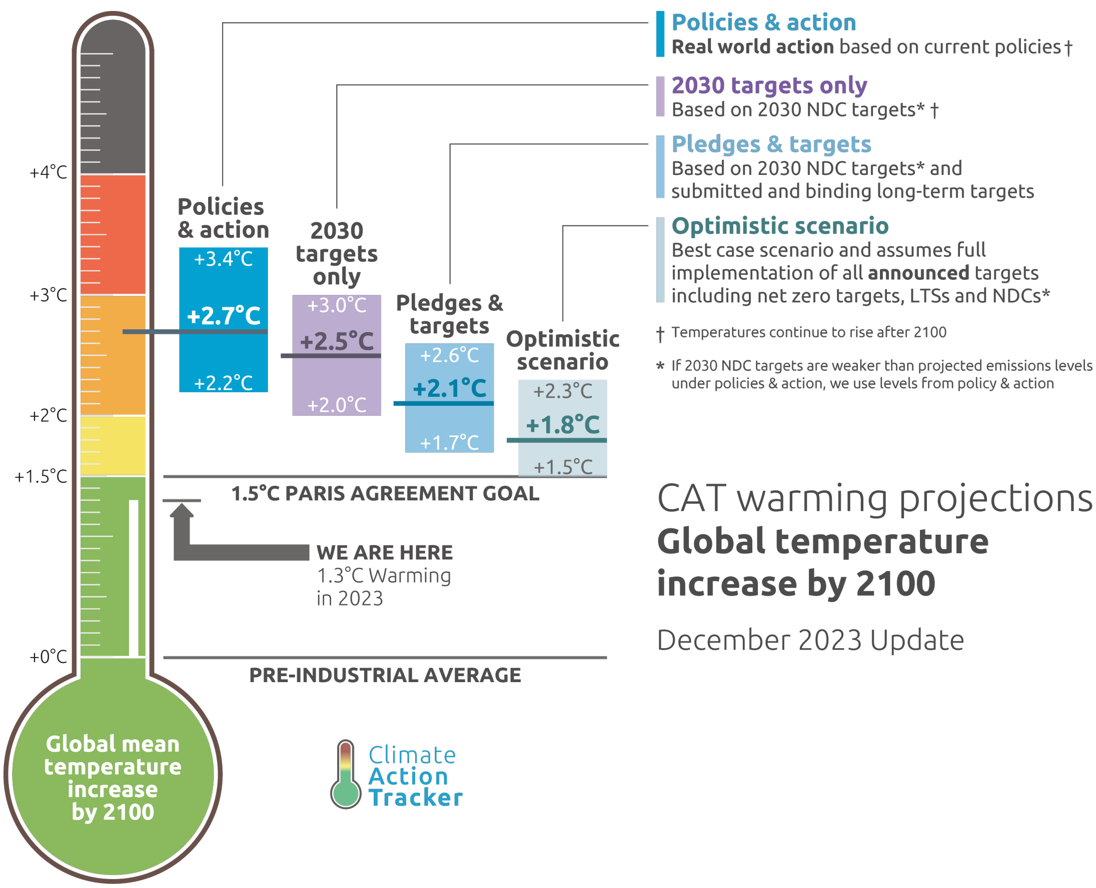


Figure 5: An infographic made by the Climate action tracker (CAT) showing the current GWL and the expected temperature increase by 2100 for different policy scenarios.

[5]Assuming conditional nationally determined contributions (NDCs) are met, range: [+1.9°C, +3.6°C] 66% probability

[6]Assuming current policy, range: [+1.9°C, +3.8°C] 66% probability

❗ CORDEX.be II Scenarios

A +2°C and a +3°C global warmer world will be explored within the CORDEX.be II project.

- The +3°C GWL is chosen as it is near the upper limit of what is currently deemed plausible.
- The +2°C GWL is chosen as it is a warming level that will likely be reached.

Note that, even though a +3°C is now considered as a worst-case scenario, unpredictable non-linear "tipping points" in the climate system could lead to a much larger warming and although unlikely, cannot be excluded. However, using a modeling approach it is not possible to include these "tipping points" in robust climate projections. Therefore, the CORDEX.be II project will simulate the +3°C GWL as its worst-case scenario and explore the most extreme simulations within this GWL, see Section 4.1.

At the lower end, limiting global warming to below +1.5°C is nowadays also considered as very unlikely (*Emissions Gap Report 2023*, 2023; Matthews & Wynes, 2022). Limiting global warming to below +2°C is still achievable if net-zero pledges are met and short-term policy action is taken (Hausfather & Moore, 2022). Even though +2°C GWL is still possible, it is at the lower end of the range of plausible global warming. The CORDEX.be II project will simulate the +2°C GWL because it is at the lower end of what is plausible while still being significantly different from the current climate.

4 Global Climate Models

Global climate models (GCMs) are used to simulate the global climate. These GCMs provide climate information at approximately 100km by 100km resolution. This is too coarse to provide detailed climate information for Belgium. Therefore, the CORDEX.be II project will use regional climate models (RCMs) to downscale (zoom in on) the CMIP6 GCMs to a 4km by 4km resolution. This process is illustrated in Figure 1.

The most recent generation of GCMs are the Coupled Model Intercomparison Project Phase 6 (CMIP6) models. CMIP6 consists of 62 GCMs from different modeling centers around the world. This diversity in GCMs is essential to capture uncertainty in the climate projections. However, the computational cost of RCM simulations limits the number of GCMs that can be downscaled in the CORDEX.be II project. In order to still capture the uncertainty and explore the most extreme yet plausible GCMs, a deliberate selection of GCMs to downscale is made.

4.1 Selection of GCMs

The choice of which GCMs to downscale are typically based on the following criteria:

- **Practical considerations**: Each RCM has technical requirements that limit which GCMs can be downscaled by that RCM. Additionally, only GCMs that provide the required data can be downscaled.
- **Model performance**: The performance of the GCMs is evaluated on the historical period.
- **Future change**: The sensitivities of GCMs with respect to changes in greenhouse gases can be very different. Ideally, GCMs are chosen that cover the entire range of sensitivities.

In the past, GCM selection was mostly dictated by practical limitations. However, due to new developments, the other criteria can play a more prominent role. For downscaling over the European domain, for instance, guidelines for the selection of GCMs were recently established (Sobolowski et al., 2023). In the CORDEX.be II project, the GCM selection partly follows these guidelines, yet with an emphasis on the Belgian domain and a focus on high climate sensitivity with respect to extreme heat and precipitation.

! GCM Selection

For different GWLs, the CORDEX.be II project selected 7 unique GCMs with the aim of including periods with extreme changes over Belgium while still covering a range of uncertainty. As an additional constraint, the selected GCMs are required to give a good representation of the past climate over Europe.

4.1.1 Practical Considerations

Firstly, some GCMs do not provide all the essential climate parameters needed as input for a RCM. These are excluded from the selection. Secondly, each RCM has technical requirements that limit which GCMs can be downscaled by that RCM. The CORDEX.be II project will use 3 RCMs: ALARO, COSMO-CLM and MAR. In Table 2, a list of compatible GCMs for each of these 3 RCMs is provided.

RCM	Compatible GCMs
ALARO	CNRM-CM6-1, CNRM-ESM2-1; Technical development ongoing to couple to more GCMs
COSMO-CLM	CMCC-CM2-SR5, EC-Earth3-Veg, MIROC6, MPI-ESM1-2-HR
MAR	All GCMs

Table 2: An overview of GCMs that can be downscaled by each RCM in the CORDEX.be II project.

4.1.2 Model performance

The model performance of CMIP6 GCMs is evaluated within the historical period and an abundance of scientific literature is available on this topic. The CORDEX.be II project will use existing model performance evaluations relevant for Europe to exclude GCMs that perform poorly. The historical model performance is evaluated on the variety of criteria, covering

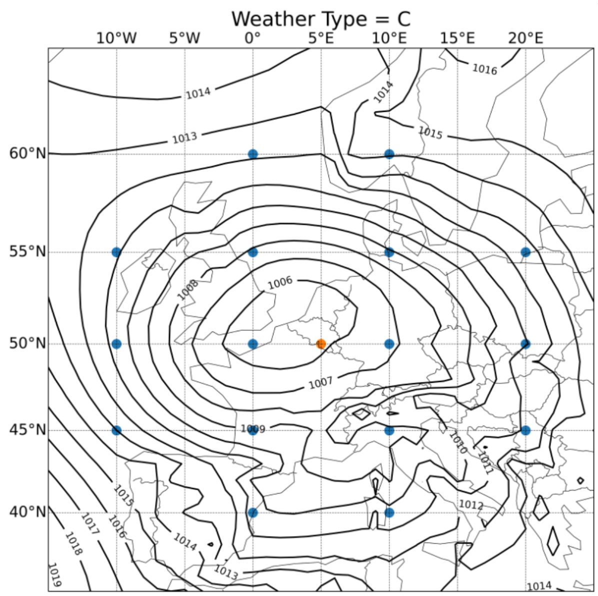
- Transient climate response (Arias et al., 2021)
- (Past) trends and spatial patterns of temperature and pressure (Brunner et al., 2020; Ribes et al., 2021)
- Global teleconnection patterns (Dalelane et al., 2023)
- Circulation (weather types and atmospheric blocking) (Brands, 2022; Davini & D'Andrea, 2020; McSweeney et al., 2015; Oudar et al., 2020; Winderlich et al., 2023)
- Storm tracks (Priestley et al., 2020)
- Seasurface temperature (Sevault et al., 2021; Sobolowski et al., 2023)
- Aerosols (Checa-Garcia et al., 2021)

The GCMs that have a plausible performance on all evaluated metrics are nicely summarized by Sobolowski et al. (2023) in the plausibility table. In the CORDEX.be II project only the GCMs that are deemed plausible for Europe are considered.

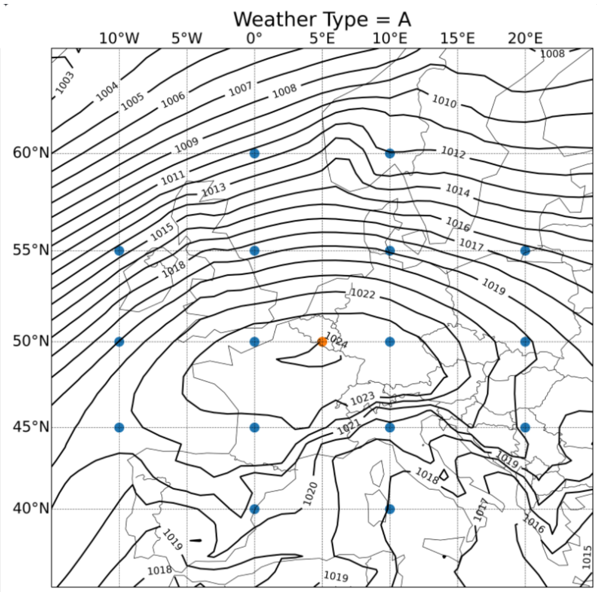
Large-scale circulation patterns are important drivers for local weather in Europe. These circulation patterns are often categorized by (Lamb) weather types (Jenkinson & Collison, 1977; Jones et al., 1993) which are defined by the mean sea level pressure. Examples of (Lamb) weather types are cyclonic and anti-cyclonic systems as illustrated in Figure 6. Accurately reproducing the frequency of weather types is important because some circulation patterns are strongly associated with extreme events. For example, heat waves often occur during anti-cyclonic situations. The evaluation of the GCMs on their ability to simulate the correct frequency of weather types over Europe was done by (Brands, 2022).

The CORDEX.be II team extended the evaluation of circulation types for Belgium specifically. The frequency of the (Lamb) weather types simulated by the GCMs is compared to the observed frequency in the historical period. Based on an evaluation metric, GCMs that perform below a certain threshold are excluded. This lead to the exclusion of 3 GCMs (FGOALS-g3, MIROC-ES2L and NorESM2-LM) that could not simulate the correct frequency of weather types over Belgium. An extensive description will be provided in the scientific publication currently being written.

Note that the underlying assumption for excluding GCMs based on historical performance is that these models will also perform poorly in the future.



(a) Cyclonic weather type: with a low surface pressure over Belgium



(b) Anticyclonic weather type: with a high surface pressure over Belgium

Figure 6: Average isobaric lines of mean sea level pressure for Belgium (orange dot) for two weather types. Blue dots represent the grid for the Lamb Weather Type classification. Data: ERA-5 1985-2014.

4.1.3 Future change

Finally, the change in the future climate relative to the recent past (1995-2014) is considered for each GCM. The change in the future climate is evaluated for the +2°C and +3°C GWLs. In the CORDEX.be II project, two rankings are made: one for extreme heat and one for extreme precipitation. These rankings: see Table 3 and Table 4, provide a list of the CMIP6 GCMs that are *potentially* the most interesting to study extremes.

RCMs simulate the climate by starting from the GCM output thus adding local detail to the GCM output. Therefore, it is the combination between the GCM and the RCM that determines the final climate simulation. This means that even if the GCM is ranked as the most extreme for heat or precipitation, there is no guarantee that the RCM-GCM combination will also simulate the most extreme climate at the higher resolution. Nevertheless, based on existing GCM-RCM downscaling data, we found that there is a strong correlation between the extreme heat and rainfall of the GCM and the one of the downscaled RCM. Therefore, the ranking provides a strong indication of which GCMs to include in order to have the highest chance of simulating large frequencies and intensities of extreme heat and precipitation events at high resolution.

4.1.3.1 Extreme heat ranking

The GCMs are ranked on their potential to downscale the most extreme heat events in Belgium by evaluating their future change in extreme heat. Three different metrics were incorporated in the ranking:

- **Heat wave Degree Days**: A metric that describes the intensity and duration of heat waves, as used by the MIRA climate report 2015.
- **HUMIDEX**: An index that considers thermal comfort through temperature and humidity.
- **Hot weather type index (HWTI):** An index that describes the change in frequency of weather types that are associated with heat high temperatures. An example of how different weather types relate to heat over the summer months can be found in Figure 7.

A combination of these indices per GWL leads to the ranking in Table 3.

A more detailed description of the extreme heat ranking procedure will be provided in the GCM selection technical report and the scientific publication both of which are currently being written.

4.1.3.2 Extreme precipitation ranking

By comparing the change in extreme precipitation between older GCM versions (CMIP5) and the RCMs that have already downscaled these GCMs, we found that a combination of average temperature change and the change in extreme (99.9th percentile) precipitation of the GCMs

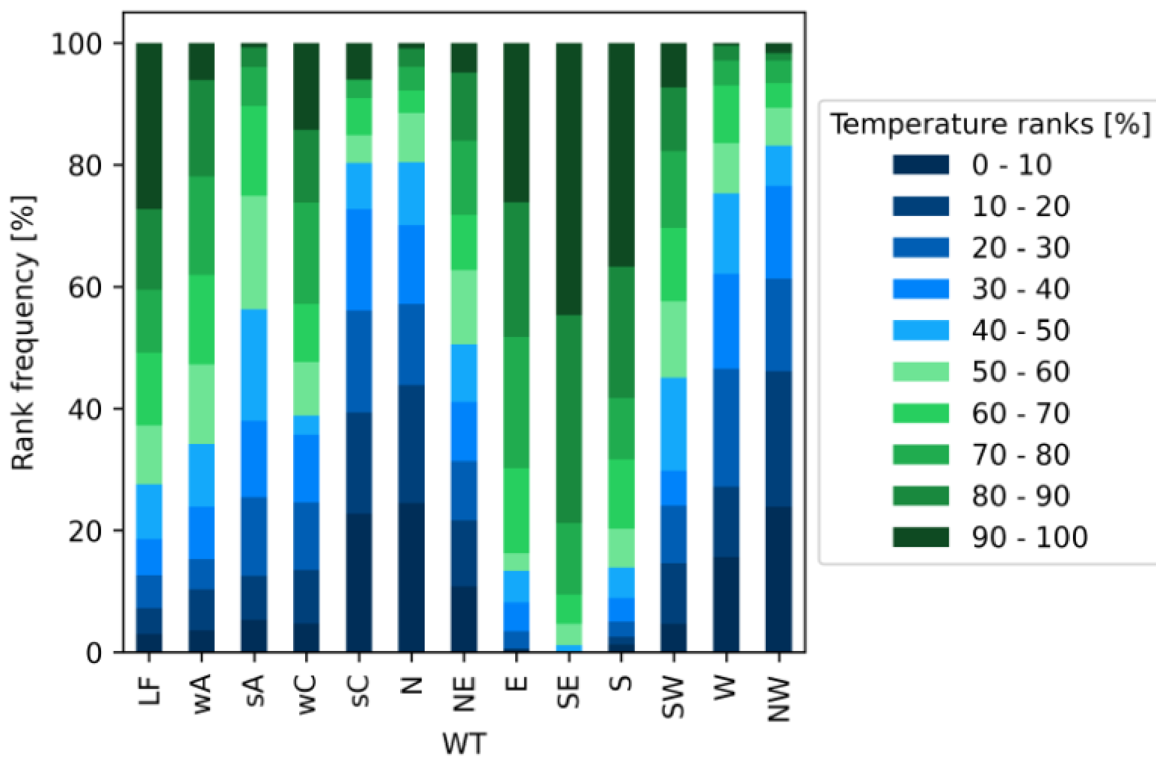


Figure 7: Occurrence of different Lamb Weather Types for different percentile ranks. The y-axis represents the frequency of a weather type within a temperature percentile (color). Typically extreme heat is linked with the South, South-East and East weather types. Data: ERA-5 (1985-2014)

Table 3: A list of the top 40 CMIP6 GCMs (per SSP) ranked based on their change in extreme heat (Heat wave degree days, HUMIDEX and HWTI) for the +2°C and +3°C GWLs compared to the recent past (1995-2014). The high ranking GCMs are potentially the most interesting to study extreme heat. Some GCMs are tied in the ranking, the actual rank is indicated in brackets.

	GWL +2°C	GWL +3°C
1	INM-CM5-0 ssp585 (1.0)	IPSL-CM6A-LR ssp585 (1.0)
2	EC-Earth3 ssp126 (2.0)	EC-Earth3-Veg ssp585 (2.0)
3	MRI-ESM2-0 ssp585 (3.5)	INM-CM5-0 ssp370 (3.0)
4	MRI-ESM2-0 ssp370 (3.5)	MRI-ESM2-0 ssp585 (4.0)
5	EC-Earth3 ssp585 (5.5)	CanESM5 ssp370 (5.0)
6	ACCESS-ESM1-5 ssp585 (5.5)	CMCC-ESM2 ssp245 (6.0)
7	CMCC-ESM2 ssp370 (7.0)	INM-CM5-0 ssp585 (7.0)
8	MRI-ESM2-0 ssp126 (8.0)	ACCESS-ESM1-5 ssp585 (8.0)
9	HadGEM3-GC31-LL ssp126 (9.0)	TaiESM1 ssp370 (9.0)
10	UKESM1-0-LL ssp245 (10.0)	UKESM1-0-LL ssp585 (10.0)
11	INM-CM5-0 ssp245 (11.0)	TaiESM1 ssp585 (11.5)
12	MRI-ESM2-0 ssp245 (12.0)	KIOST-ESM ssp585 (11.5)
13	MPI-ESM1-2-LR ssp370 (13.0)	NorESM2-MM ssp370 (13.0)
14	NorESM2-MM ssp245 (14.0)	TaiESM1 ssp245 (14.5)
15	CNRM-CM6-1 ssp126 (15.0)	EC-Earth3 ssp585 (14.5)
16	INM-CM4-8 ssp370 (16.0)	EC-Earth3 ssp370 (16.0)
17	NorESM2-MM ssp370 (17.0)	CanESM5 ssp585 (17.0)
18	EC-Earth3-Veg ssp370 (18.0)	MRI-ESM2-0 ssp370 (18.0)
19	IPSL-CM6A-LR ssp585 (19.0)	TaiESM1 ssp126 (19.0)
20	EC-Earth3 ssp370 (20.0)	CNRM-ESM2-1 ssp585 (20.0)
21	CNRM-ESM2-1 ssp126 (21.5)	CNRM-ESM2-1 ssp245 (21.0)
22	HadGEM3-GC31-LL ssp585 (21.5)	EC-Earth3-Veg ssp245 (22.0)
23	MIROC6 ssp370 (23.0)	IPSL-CM6A-LR ssp370 (23.0)
24	GFDL-ESM4 ssp245 (24.5)	ACCESS-ESM1-5 ssp245 (24.0)
25	EC-Earth3-Veg ssp126 (24.5)	CMCC-ESM2 ssp585 (25.0)
26	HadGEM3-GC31-MM ssp585 (26.0)	EC-Earth3-CC ssp585 (27.0)
27	HadGEM3-GC31-MM ssp126 (27.5)	CMCC-ESM2 ssp370 (27.0)
28	TaiESM1 ssp585 (27.5)	ACCESS-ESM1-5 ssp370 (27.0)
29	INM-CM5-0 ssp370 (29.0)	HadGEM3-GC31-MM ssp126 (29.5)
30	ACCESS-ESM1-5 ssp245 (30.0)	CanESM5 ssp245 (29.5)
31	INM-CM4-8 ssp245 (31.0)	CNRM-CM6-1 ssp245 (31.0)
32	CanESM5 ssp370 (32.0)	GFDL-CM4 ssp585 (32.5)
33	ACCESS-CM2 ssp245 (33.0)	IPSL-CM6A-LR ssp245 (32.5)
34	ACCESS-CM2 ssp126 (34.0)	MIROC6 ssp585 (34.0)
35	UKESM1-0-LL ssp585 (35.0)	MIROC6 ssp370 (35.5)
36	GFDL-CM4 ssp245 (36.5)	CNRM-CM6-1 ssp370 (35.5)
37	GFDL-ESM4 ssp585 (36.5)	INM-CM4-8 ssp585 (37.0)
38	CMCC-ESM2 ssp245 (38.5)	GFDL-ESM4 ssp585 (38.0)
39	EC-Earth3-Veg-LR ssp245 (38.5)	EC-Earth3-Veg ssp370 (39.0)
40	CNRM-ESM2-1 ssp585 (40.0)	UKESM1-0-LL ssp370 (40.0)

is a good indicator of the change in extreme precipitation at higher resolution. We tested the sensitivity of this methodology with respect to the definition of extreme rainfall, GCM and RCM groups, and regions over Europe and found it to be very robust. Based on the (CMIP5) relations, we have then estimated the change in extreme precipitation for the CMIP6 models, using their changes in average temperature and extreme precipitation (99.9th percentile). A ranking of these CMIP6 models, in order of their estimated change in extreme rainfall, is shown in Table 4. A more detailed description of the extreme precipitation ranking procedure will be provided in the GCM selection technical report and the scientific publication both of which are currently being written.

For a more detailed description of the ranking see the GCM selection technical report.

4.2 Final selection

The final selection of GCMs is made per RCM by combining the practical limitations, model performance and future change with the aim to:

- Exclude underperforming GCMs
- Cover a wide range of uncertainty - Include dry and wet GCMs, warm and cold GCMs
- Include the most extreme GCMs for extreme heat and precipitation.

The first is achieved by excluding GCMs that are not compatible with the RCM or that had the poorest comparison with past observations over Europe. The second is achieved by selecting GCMs proposed by the EURO-CORDEX guidelines (Sobolowski et al., 2023) which cover a wide spread of uncertainty. The third is achieved by selecting the GCMs that are ranked highest for extreme heat and precipitation in the +3°C GWL. A focus on the +3°C ranking was chosen because these GCMs are the most extreme models that are still within the range of plausible global warming, see Section 3.3.

Below, the final selection of GCMs per RCM is described in more detail, and is shown in Table 5.

4.2.1 Intercomparison

For intercomparison purposes, one GCM (EC-Earth3-Veg) is selected for all 3 RCMs. This GCM is selected because it is performing well over Europe and it is compatible with all 3 RCMs. The SSP5-8.5 scenario from this GCM is selected because it has the highest ranking for extreme heat and precipitation when compared to the other SSPs for this GCM.

Table 4: A list of the top 40 CMIP6 GCMs (per SSP) ranked based on their change in average temperature and extreme precipitation (99th percentile) for the +2°C and +3°C GWLs.

	GWL +2°C	GWL +3°C
1	MIROC6 ssp585	E3SM-1-0 ssp585
2	EC-Earth3 ssp585	EC-Earth3 ssp585
3	MIROC6 ssp370	EC-Earth3 ssp370
4	MIROC6 ssp245	ACCESS-CM2 ssp370
5	NESM3 ssp585	MIROC6 ssp585
6	E3SM-1-0 ssp585	ACCESS-ESM1-5 ssp585
7	EC-Earth3 ssp370	ACCESS-ESM1-5 ssp370
8	GFDL-CM4 ssp585	ACCESS-CM2 ssp245
9	EC-Earth3 ssp126	MIROC-ES2L ssp370
10	ACCESS-CM2 ssp126	GFDL-ESM4 ssp370
11	GFDL-CM4 ssp245	GFDL-CM4 ssp585
12	ACCESS-CM2 ssp585	EC-Earth3-AerChem ssp370
13	NorESM2-LM ssp245	BCC-CSM2-MR ssp370
14	MIROC-ES2L ssp245	MIROC-ES2L ssp585
15	ACCESS-ESM1-5 ssp585	GFDL-ESM4 ssp585
16	ACCESS-ESM1-5 ssp126	EC-Earth3 ssp245
17	TaiESM1 ssp585	TaiESM1 ssp585
18	ACCESS-CM2 ssp370	HadGEM3-GC31-LL ssp585
19	MIROC-ES2L ssp370	NorESM2-LM ssp585
20	EC-Earth3 ssp245	TaiESM1 ssp370
21	TaiESM1 ssp370	ACCESS-CM2 ssp585
22	GFDL-ESM4 ssp585	NESM3 ssp585
23	KACE-1-0-G ssp370	BCC-CSM2-MR ssp585
24	ACCESS-ESM1-5 ssp245	UKESM1-0-LL ssp585
25	MIROC-ES2L ssp585	TaiESM1 ssp245
26	GFDL-ESM4 ssp370	EC-Earth3-Veg ssp585
27	HadGEM3-GC31-LL ssp585	MPI-ESM1-2-HR ssp370
28	EC-Earth3-AerChem ssp370	INM-CM5-0 ssp585
29	GFDL-ESM4 ssp245	CNRM-ESM2-1 ssp585
30	ACCESS-CM2 ssp245	KACE-1-0-G ssp585
31	BCC-CSM2-MR ssp245	CMCC-CM2-SR5 ssp370
32	INM-CM5-0 ssp370	CAMS-CSM1-0 ssp585
33	BCC-CSM2-MR ssp370	MPI-ESM1-2-HR ssp585
34	UKESM1-0-LL ssp245	HadGEM3-GC31-LL ssp245
35	NESM3 ssp245	INM-CM5-0 ssp370
36	UKESM1-0-LL ssp370	UKESM1-0-LL ssp370
37	NorESM2-LM ssp370	IITM-ESM ssp585
38	HadGEM3-GC31-LL ssp126	CMCC-CM2-SR5 ssp585
39	KACE-1-0-G ssp245	KACE-1-0-G ssp245
40	ACCESS-ESM1-5 ssp370	KACE-1-0-G ssp370

4.2.2 MAR

Since the MAR model has the flexibility to downscale all CMIP6 GCMs, 5 (including EC-Earth3-Veg) out of the 9 GCMs that are recommended by the CORDEX guidelines for Europe (Sobolowski et al., 2023) are selected. These GCMs are recommended because they are deemed plausible for Europe and cover a wide range of uncertainty, thus including both wet and dry GCMs and both warm and cold GCMs. Per GCM, MAR will downscale 4 different SSPs: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.

To include the most extreme GCMs for extreme heat and precipitation, the GCMs that ALARO and COSMO-CLM plan to downscale are selected based on the rankings in Table 3 and Table 4.

4.2.3 COSMO-CLM

COSMO-CLM plans to downscale 2 GCMs, one of which is EC-Earth3-Veg. The other GCM is selected based on the extreme heat ranking in Table 3.

4.2.4 ALARO

ALARO plans to downscale 4 GCMs in total, including EC-earth3-Veg. CNRM-CM6-1 is also selected because it is already compatible with ALARO. The remaining two GCMs are selected based on the extreme precipitation rankings in Table 4.

4.2.5 Overview

In Table 5, the selection of GCMs per RCM is shown with the main reason for their selection. Note that this selection is still subject to change due to technical, practical or computational limitations that may arise during the simulations.

GCMs / RCMs	ALARO	COSMO-CLM	MAR
EC-Earth3-Veg	histo, ssp585, ssp245	histo, ssp585, ssp245	histo, ssp585, ssp370, ssp245, ssp126
CMCC-CM2-SR5			histo, ssp585, ssp370, ssp245, ssp126
CNRM-CM6-1-HR	histo, ssp585, ssp245		
MIROC6		histo, ssp585, ssp245	histo, ssp585, ssp370, ssp245, ssp126
MPI-ESM1-2-HR			histo, ssp585, ssp370, ssp245, ssp126

GCMs / RCMs	ALARO	COSMO-CLM	MAR
NorESM2-MM			histo, ssp585, ssp370, ssp245, ssp126
TBD	histo, ssp585, ssp245		

Table 6: Proposed RCM-GCM matrix for the CORDEX.be II project. histo: Historical period which is the recent past 1995-2014. For a status update of the simulation see the CORDEX.be II website

5 Conclusion

RCM-simulations are not only computationally expensive, they are also time consuming to run. Therefore, once these simulations have started, decisions on the scenarios and the selected GCMs to downscale (zoom) can not be changed. Therefore, it is important that the chosen scenarios and selected GCMs are in line with the project goals and the stakeholders needs.

In the report, a few key stakeholder priorities are identified. An important priority being the exploration of the extreme events within worst-case scenarios that are still plausible. These priorities are used to guide the selection of the future periods and GCMs that the RCMs will downscale.

Two future periods are selected: a +2°C and a +3°C GWL. These periods are chosen because they are at the upper and lower end of peak global warming that is currently deemed plausible this century.

A comprehensive analysis of CMIP6 GCMs is performed. The GCMs are selected based on their practical limitations, model performance and future change. The goal of the selection is to cover a wide range of uncertainty and to include the most extreme GCMs for extreme heat and precipitation per GWL. The final selection of GCMs is shown in Table 5.

The three RCMs (ALARO, COSMO-CLM and MAR) will downscale the selected GCMs for the recent past and these two GWLs in 20-year slices. This will provide input for impact models enabling a detailed exploration of the future climate in Belgium for these two GWLs. Within the CORDEX.be II project, hydrological and urban impact models will be run. Finally, these RCM simulation will be the basis for Tales of future weather, a series of stories about the future climate in Belgium we aim to co-create with interested stakeholders.

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Table 5: Final selection of GCMs for the CORDEX.be II project with the main reason for their selection. TBD - To be determined depending on the ongoing technical developments.

RCM	Selected GCM	Reason for selection
ALARO	CNRM-CM6-1-HR	Practical
	EC-Earth3-Veg	Extreme: heat ranking & Practical: RCM Interco...
	TBD	Extreme: precipitation ranking
COSMO-CLM	EC-Earth3-Veg	Extreme: heat ranking & Practical: RCM Interco...
	MIROC6	Extreme: heat ranking
MAR	CMCC-CM2-SR5	Spread: EURO-CORDEX guidelines
	EC-Earth3-Veg	Extreme: heat ranking & Practical: RCM Interco...
	MIROC6	Spread: EURO-CORDEX guidelines
	MPI-ESM1-2-HR	Spread: EURO-CORDEX guidelines
	NorESM2-MM	Spread: EURO-CORDEX guidelines

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