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D7.3

Future climate scenarios: Sea level rise and Arctic sea ice extent

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X	PU	Public
	PP	Restricted to other programme participants
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	CO	Confidential, only for members of the consortium

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1 Introduction

This deliverable is part of Work Package 7 (WP7) called “sea level rise, infrastructure and coastal flooding” from the H2020 project called “REmote Climate Effects and their Impact on European sustainability, Policy and Trade” (RECEIPT). As part of WP7 the deliverable 7.2 provides the assessment of flood risk under the current climate for three storylines. These storylines cover three recent events that resulted in coastal floods in Europe: storm Xaver that hit the southern North Sea in December 2013, storm Xynthia that hit the Atlantic coast of France in February 2010 and the November 2002 storm surge in Emilia-Romagna, Italie. This deliverable 7.3 provides the scenarios of sea level rise that will be used as part of deliverable 7.4 to assess how sea level rise will increase the impact of these storms on the European coastal infrastructure.

Reports from the Intergovernmental Panel on Climate Change (IPCC) regularly provide an assessment of the sea level literature and future sea level scenarios. Different methods exist to make these scenarios. Simple semi-empirical models that relate sea level rise to global variables like the radiative imbalance at the top of the atmosphere or global surface air temperature (GSAT) have been used to make global sea level rise projections (Rahmstorf 2007). Some simple model frameworks have also been designed to make the best use of sea level observations (Wong et al. 2017) and long term commitments (Mengel et al. 2016). However, the process-based method is trusted the most by IPCC (AR5, Church et al. 2013). This method relies on the climate models from the Climate Model Intercomparison Projects (CMIP). It models each contributor to sea level rise in the most physically consistent possible manner. The process-based method, as implemented by the IPCC, still has its limitations. As acknowledged by recent IPCC reports, the *likely range* of sea level projections has a probability, conditional on a given emission scenario, of 66% or more (AR5) or exactly 66% (SROCC, Pörtner et al. 2019) for SLR to fall within this range. The SROCC report warned that even though their highest sea level scenario, the upper bound of the *likely range* for the RCP8.5 emission scenario, gave a sea level rise of 1.1 m in 2100 relative to 1986-2005, a rise of 2 m in 2100 couldn’t be ruled out. The difficulty arises in particular when assessing relatively young fields in which knowledge is not yet settled, like ice-sheet science (Pattyn 2018). The results of structured expert judgements about future ice-sheet mass loss have shown a much larger uncertainty and more expected mass loss than accounted for in IPCC projections (Bamber et al. 2019). The observed ice sheet mass loss has been shown to track the high-end of the IPCC AR5 projections (Slater, Hogg, and Mottram 2020) and some ice sheet experts have made the case that IPCC projections could underestimate future ice sheet mass loss, especially for the high greenhouse gas emission scenarios (Siegert et al. 2020).

Given these limitations and the global focus of the IPCC reports it seems important to design regional sea level scenarios that meet the particular needs of the diverse user groups (Hinkel et al. 2019). For some stakeholders focused on determining further investment in public flood risk management activities (such as the Environment Agency's Long Term Investment Planning processes) the require is for the most plausible SLR scenarios. For climate stress testing (for example for financial disclosure as set out in the Bank of England Climate Stress tests), the broad range of sea level rise scenarios are more applicable to help understand the range of future risk. For some individual infrastructure owners (such as Port of Rotterdam) the case for including climate change within their development planning process remains less mature. In this case higher end scenarios are needed to ensure the decisions made are robust but supported alongside low-end scenarios to demonstrate action is needed regardless of the uncertainty in future sea level rise. For the most advanced and critical infrastructure providers (such as nuclear industry) the plausible high ends scenarios underpin the long-term safety

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case. We respond to these board requirements here in supporting the WP7 storylines through a view of the future sea level rise that:

1- Includes careful consideration of regional processes relevant for the European coast
2- Provides projections 100 years into the future
3- Considers a broad range of cases, from very optimistic to very pessimistic but avoid too controversial assumptions
4- Is based on state-of-the-art information

These are the steps we take to meet these expectations:

1- We include a careful consideration of the ocean dynamic sea level changes and a diversity of approaches to project the Antarctic dynamic contribution to sea level because ocean dynamics and Antarctic dynamics are shown to be particularly relevant for the European coast.
2- The projections extend up to 2125 instead of the usual 2100
3- We consider a broad range of cases by extending the range of percentiles that we use (5-95th instead of 17-83rd in SROCC), by considering extreme but trustworthy models of ocean dynamics and by using two different approaches to project Antarctic dynamics. To avoid controversial assumptions, we do not include the Marine Ice Cliff Instability in the projections.
4- Our projections are based on the new state-of-the-art CMIP6 climate model ensemble that we compare with CMIP5

An overview of the different sea level rise contributors considered in our sea level scenarios and how sea level rise fits into the WP7 goals is shown in Figure 1.

While assessing the impact of Arctic sea-ice retreat on shipping and the potential disruption or opportunities for the European harbors was one of the goals of WP7, the storylines that we decided to investigate focus on sea level rise and coastal floods (RECEIPT D7.2: The assessment of flood risk under the current climate for three storylines). Therefore, this report is mainly about sea level rise scenarios. However, some externally designed Arctic sea-ice scenarios were identified that we could use if we decide to investigate this topic.

The remainder of this report is structured as follows. In section 2 we describe how global thermosteric and ocean dynamic sea level from the CMIP6 ensemble are obtained and how they compare to CMIP5. In this section we also describe which climate models are used to project ocean dynamics in the sea level scenarios. The sea level scenarios, the core of this deliverable, are described in section 3. Section 4 gives some information about which already developed Arctic sea-ice scenarios could be used within WP7. We finish with a conclusion in section 5.

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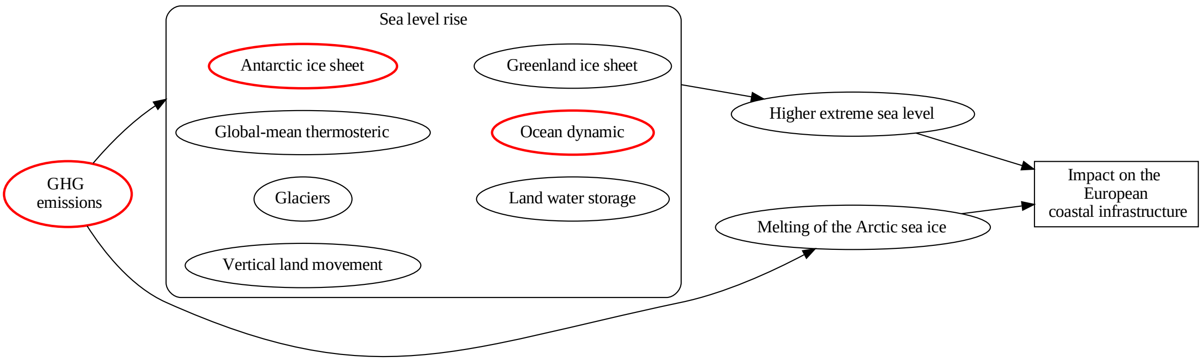

Figure 1: Overview showing how sea-level rise and Arctic sea ice, the topics of this deliverable, fit into Work Package 7. The physical mechanisms contributing to sea level are also listed. Processes circled red are the key elements used to design the sea-level scenarios.

2 Global thermosteric and ocean dynamic sea level from CMIP5 and CMIP6

2.1 Method

Two contributors to sea level are directly available from the outputs of the models taking part in CMIP. These are (1) the global-mean thermosteric sea-level change, often called thermal expansion, which is given by the CMIP variable *zostoga,* and (2) the spatially varying ocean dynamic sea level given by the variable *zos*. These two physical processes are separated in the CMIP model outputs because while *zos* is a model variable, *zostoga* is not. This is because the majority of climate models make the Boussinesq approximation and conserve volume rather than mass. In particular, they do not properly represent the expansion and contraction of the ocean water when its density changes. This is not a serious error and the global impact of changes in density can be computed offline after the model simulation is completed by integrating the global density changes (Greatbatch 1994; Griffies and Greatbatch 2012). Global-mean sea level is influenced by changes in both temperature (thermosteric) and salinity (halosteric). However, global-mean halosteric sea-level change is practically zero in the real ocean. Therefore global-mean steric sea-level changes are usually diagnosed using global-mean thermosteric sea-level change only. This eliminates the risk of including spurious global-mean halosteric sea-level changes (Gregory et al. 2019). Ocean dynamic sea level is "the local height of the sea surface above the geoid with the inverse barometer correction applied" (Gregory et al. 2019) and it is modeled directly by the current climate models. More simply explained, ocean dynamic sea level is the sea level anomaly that is due to wind stresses, ocean currents and local temperature and salinity.

Besides running the climate models for the future with different greenhouse gas scenarios, each model also needs to run a long spin-up with stationary forcings, a *historical* experiment and a pre-industrial control (*piControl)* experiment. The *historical* experiment starts after the spin-up and covers the years 1850-2005 in CMIP5 and 1850-2014 in CMIP6. It includes all known time-varying climate forcings for this period (e.g., anthropogenic and volcanic aerosols and greenhouse gases, solar radiation). The future projections use the end of the *historical* simulations as initial conditions and run until 2100 except for a few models that run up to 2300. The *piControl* simulation branches out of the spin-up at the same time as the historical simulation and is at least as long as the total duration of the historical and scenario simulations, so 250 or 450 years. Contrary to the *historical* simulation, *piControl* has no changes in the forcing.

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We downloaded and post-processed the data from all available CMIP5 and CMIP6 models. An overview of the number of models available for each climate scenario is given in Table 1. A lot more detailed information about the variant (for a given experiment, the variant number is used to uniquely identify each simulation of an ensemble of runs contributed by a single model), grid and version of datasets used in this report is available as supplementary csv files with an example given in Table 4.

Table 1: Number of models available for each emission scenario, variable (zostoga: global-mean thermosteric sea level, zos: ocean dynamic sea level) and CMIP phases.

CMIP5			CMIP6		
Emission scenario	# models for zostoga	# models for zos	Emission scenario	# models for zostoga	# models for zos
			SSP1-1.9	7	12
RCP2.6	18	20	SSP1-2.6	21	29
RCP4.5	24	29	SSP2-4.5	21	29
RCP8.5	24	30	SSP5-8.5	21	30

The downloading and post-processing of *zostoga* is relatively simple because since it is globally averaged it has only one dimension (time). Here are the three post-processing steps that we perform:

1- We combine the monthly data from all the models that use different time units and references into one file containing yearly averaged data using the same time variable for all models. This makes the data easy to share and analyze.

2- We use the *piControl* simulations of each model to remove the linear drift in the *historical* and future scenario simulations. This relies on the reasonable assumption that the drift is not sensitive to the external forcing (Hobbs, Palmer, and Monselesan 2016). This step has a small impact on the ensemble mean projections (<1cm for *zostoga* in 2100) but it reduces the divergence between models by a few centimeters.

3- Some models from CMIP5 were found to have non-physical discontinuities. These are filtered out.

The zos variable has three dimensions (time, latitude, longitude) which makes it more difficult to analyze. The first two steps of the post-processing are the same as for *zostoga*. Then, since all models discretize the ocean on different grids, the data needs to be regridded to the same grid to be able to analyze the models together. We choose a regular 1ºx1º grid for that. This is performed in a computationally efficient way using the open-source library xESMF with a bilinear method for most models and a nearest-neighbor method for the few models for which the bilinear approach does not work. Additionally, the land/sea mask also has differences between models. This creates some issues close to the coast or in almost enclosed seas like the Baltic and the Mediterranean seas where some models have outputs, but some have not. Two choices are possible for these areas, (1) spatial extrapolation of the available data to where there is no data, or (2) keep a different land/sea separation for each model. Method (2) is the usual choice (Church et al. 2013) but leads to awkward spatial discontinuities in maps of ensemble mean and standard deviation. Therefore, we chose option (1) here.

2.1.1 Code and data availability

The synda library (https://prodiguer.github.io/synda/) was used to download CMIP5 and CMIP6 data from the ESGF nodes. The code to prepare and analyze the data was written in

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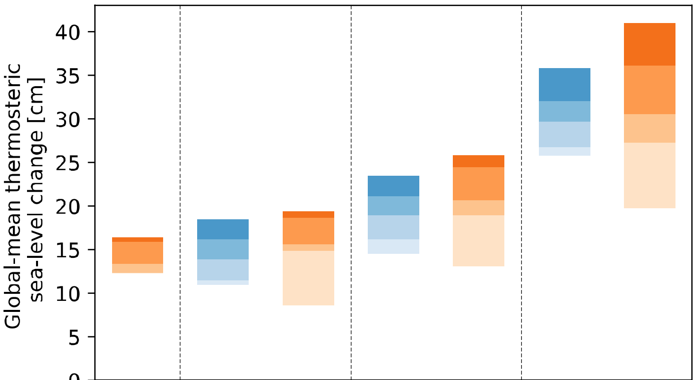
Python and is available on GitHub under the open source GPLv3 license (https://github.com/dlebars/CMIP_SeaLevel). The following open-source libraries were used: Xarray to read and write NetCDF files, xESMF (https://github.com/pangeo-data/xESMF) for the regridding, numpy and Pandas.

The data is available at Zenodo (10.5281/zenodo.5347691).

2.2 Results

2.2.1 Global-mean thermosteric sea-level change (*zostoga*)

The results of global mean thermosteric sea-level rise for the end of the century are summarized in Figure 2 where the quantiles are computed from linearly interpolating in the quantile dimension between members of the model ensembles. Given the limited ensemble sizes (7 for SSP1-1.9, around 20 for the others, Table 1), quantile estimates should be taken as indicative. The model ensembles are interpreted probabilistically here but given the small ensemble size we should be careful about this interpretation. In CMIP6 scenarios that have an equivalent CMIP5 scenario, the ensemble medians increase only slightly, 1.7, 1.7 and 0.9 cm respectively for 2.6, 4.5 and 8.5 scenarios. The ensemble spread increased for all scenarios. This is surprising since additional development time and the fact that simulations were run later, closer to 2100, would be expected to have reduced the divergence. This seems to be the result of most models having slightly larger values in CMIP6 than in CMIP5 except for two models that seem much lower and could be considered outliers: INM-CM4-8 and INM-CM5-0 (orange and green lines in right panel of Figure 3).



	SSP1-1.9	RCP2.6	SSP1-2.6	RCP4.5	SSP2-4.5	RCP8.5	SSP5-8.5
Percentile: 95	16.4	18.5	19.4	23.5	25.8	35.8	41.0
Percentile: 83	15.9	16.2	18.7	21.1	24.5	32.1	36.1
Percentile: 50	13.4	13.9	15.6	19.0	20.7	29.7	30.6
Percentile: 17	12.4	11.5	14.9	16.2	19.0	26.8	27.3
Percentile: 5	12.3	11.0	8.6	14.6	13.1	25.8	19.8

Figure 2: Global-mean thermosteric sea level change [cm] between 2095-2099 and 1986-2005. CMIP5 and CMIP6 scenarios are represented in blue and orange respectively.

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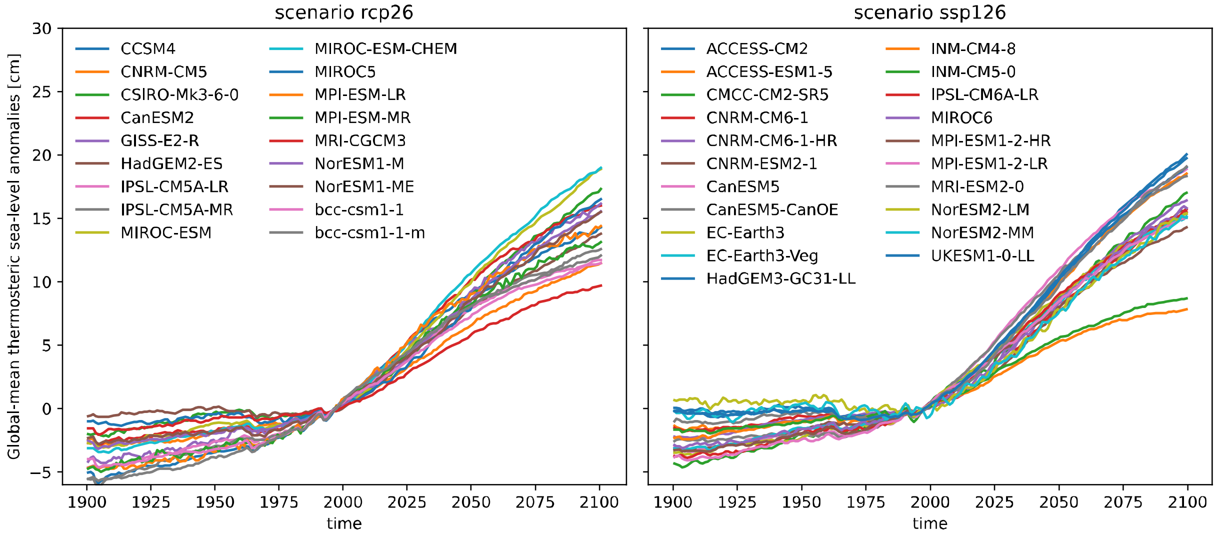

Figure 3: Anomalies of global-mean thermosteric sea level under two climate scenarios: CMIP5 RCP2.6 (left) and CMIP6 SSP1-2.6 (right). Each line represents the result of one climate model with the model names in the legend. The reference period is 1986-2005.

2.2.2 Ocean dynamic sea-level change (*zos*)

The general pattern of ocean dynamic sea level change in coupled atmosphere-ocean general circulation models, shown in Figure 4, is reasonably well understood but large disagreements between models remain (Todd et al. 2020). In the North Atlantic, reduced heat loss and increased precipitation over the high-latitude provides buoyancy, weakens the Atlantic Meridional Overturning Circulation (AMOC) and leads to a meridional dipole in sea level. In agreement with Lyu, Zhang, and Church 2020 we find that CMIP6 has a very similar ocean dynamic pattern as CMIP5 with a larger magnitude (see Figure 4 for RCP4.5/SSP2-4.5). This is the case for all emission scenarios. This amplification is probably due to a faster climate warming in CMIP6 compared to CMIP5.

The pattern of ocean dynamic sea level change is also amplified at the European coast (Figure 5). This means that under CMIP6 ocean dynamics tends to accelerate sea level rise at the European coast. The fact that the pattern of the difference between CMIP6 and CMIP5 (lower panel in Figure 4 and right panel in Figure 5) is the same as the pattern of the sea level changes themselves shows that it is an amplification of the existing CMIP5 pattern that results in the CMIP6 field. While the global pattern is understood by the scientific community, the regional pattern hasn't received much attention. We see that ocean dynamic sea level change is larger along the Norwegian coast, in the North Sea and along the shelf break North and West of the British Isles. The Atlantic coast of Spain and Portugal and the Mediterranean Sea are relatively less impacted by ocean dynamics although this process still contributes to sea level rise there. This meridional gradient might be because large scale buoyancy forcing are advected southward along the shelf break and diluted on the way.

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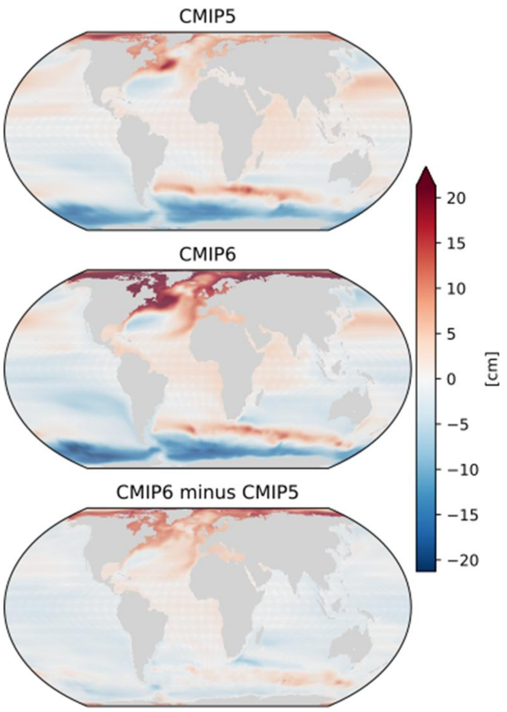

Figure 4:Ensemble averaged Ocean dynamic sea level for the scenarios RCP4.5 (CMIP5) and SSP2-4.5 (CMIP6). The difference between 2095-2099 and 1986-2005 is shown.

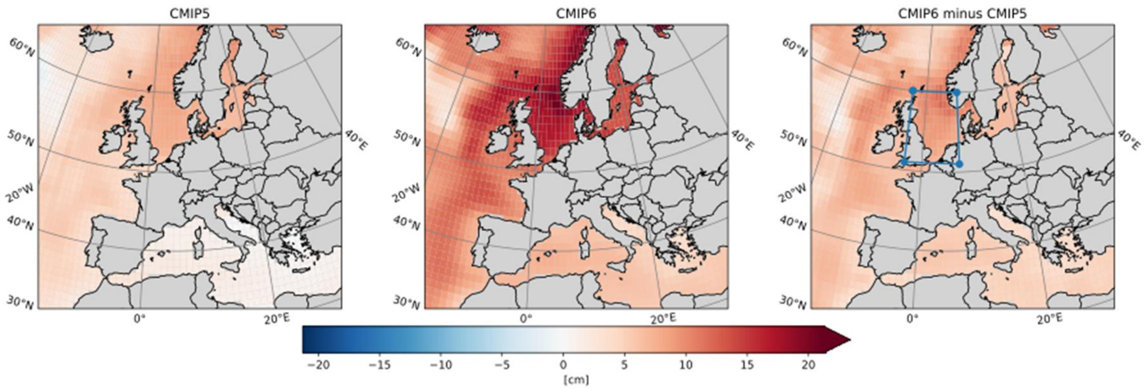

Figure 5: Same as previous figure but for Europe. The North Sea region over which a spatial average is computed for the Figure 6 time series is indicated in the right panel.

The time evolution of this component is also important for sea level projections. Because the first storyline of WP7 focusses on the Xaver storm that hit Northern Europe in 2013, we focus our attention to the North Sea. The spatial average ocean dynamic sea level in the North Sea is shown in (Figure 6). Over the 20th century there is a small sea level rise in CMIP5 followed by a faster rise between 2000 and 2080 and a drop after 2080. In 2100 ocean dynamic contributes around 7.5 cm to sea level rise compared to the reference period of 1986-2005. In contrast, the CMIP6 ensemble shows no rise during the 20th century followed by a fast rise between 2000 and 2075 and slower rise afterward.

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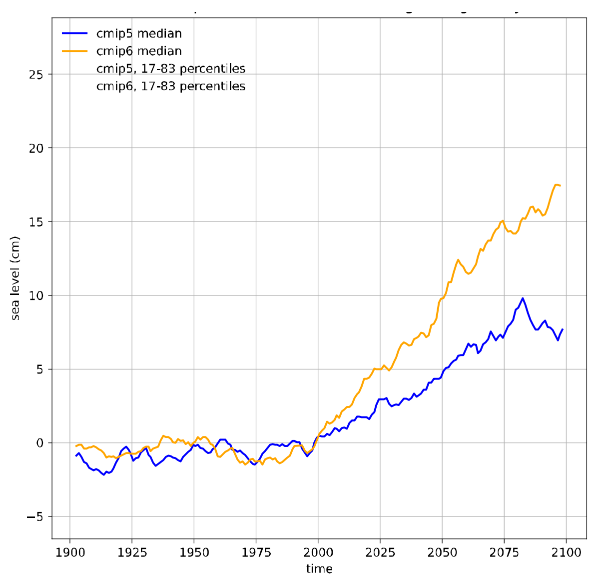

Figure 6: Ocean dynamic sea-level change averaged in the North Sea for the scenarios RCP4.5 (CMIP5) and SSP2-4.5 (CMIP6). The reference period is 1986-2005 and a low-pass filter of five-year running average is applied.

For the sea-level scenario design one of the choices is the model used to represent ocean dynamics (see description in section 3). In Figure 7 we show the selection of extreme models and how they compare with other models of the ensemble. This selection is made for the North Sea because it is to study storm Xaver. It is roughly representative of the entire European Atlantic coast but is expected to be very different elsewhere. For SSP1-2.6 we choose GISS-E2-1-G that models a slow sea-level drop in contrast with most other models. For SSP5-8.5 we choose the UKESM1-0-LL model that projects a contribution of ocean dynamic sea level much larger than the average.

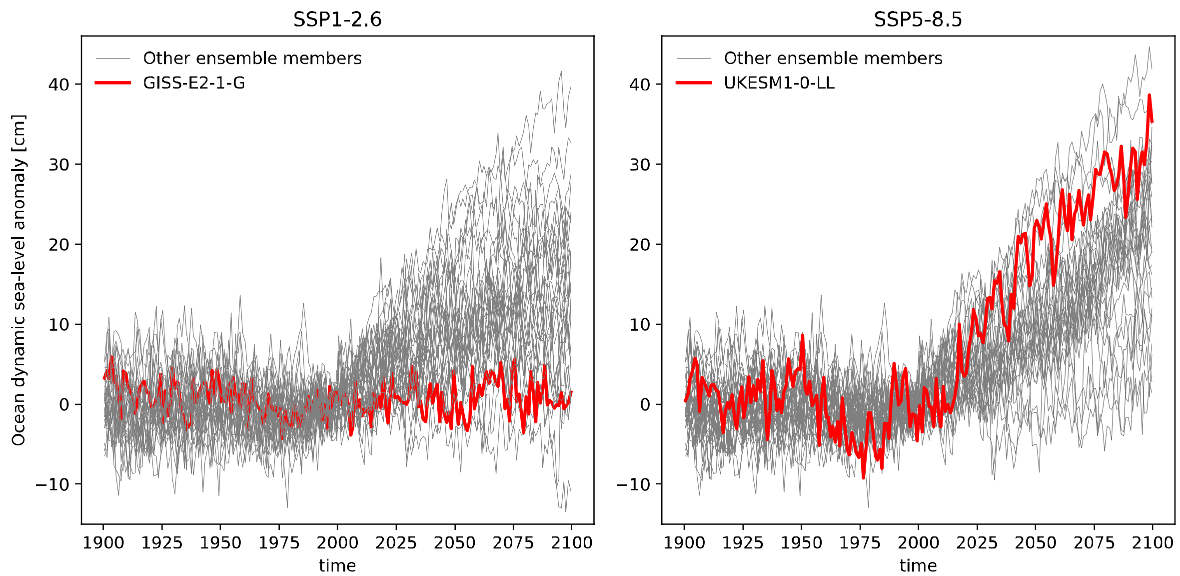

Figure 7: Selection of models with low (left) and high (right) ocean dynamic sea-level rise for SSP1-2.6 and SSP5-8.5 respectively.

2.3 Discussion

The fact that the median global-mean thermosteric sea level in 2100 is only slightly larger in CMIP6 compared to CMIP5 is rather surprising given the large increase in GSAT in 2100 in CMIP6

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compared to CMIP5 due to both larger Effective Radiative Forcing in the SSP scenarios compared to the RCP (section 4.6.2.2 in AR6) and due to larger climate sensitivity in CMIP6 climate models (Liang, Gillett, and Monahan 2020; Tokarska et al. 2020). The explanation is twofold. First what matters for global-mean thermosteric sea level in 2100 is not the temperature in 2100 but the time integrated temperature anomaly because the ocean has a slow response to changes in GSAT. By that measure CMIP6 and CMIP5 are a lot closer because differences in temperature primarily arise later in the century (Hermans et al. 2021). The second reason is that CMIP6 seems to have smaller ocean heat uptake efficiency than CMIP5 (Hermans et al. 2021). This is consistent with the underestimated global-mean thermosteric sea level change in CMIP6 compared to observations and CMIP5 during the 20th century (Jevrejeva, Palanisamy, and Jackson 2020). The reason for this change in ocean heat uptake efficiency is not yet known.

The situation is different for ocean-dynamic sea-level changes because they are driven by regional wind and buoyancy changes at the ocean surface that react to GSAT more rapidly than thermosteric sea level (Perrette et al. 2013; Yuan and Kopp 2021). This results in a much larger divergence between CMIP5 and CMIP6. The speed of ocean-dynamic sea-level rise in CMIP6 is impressive, we see in Figure 6 a sea-level rise of around 15 cm in 75 years for the SSP2-4.5 scenario, between 2000 and 2075. This is an average of 2 mm/year which is equal to the speed at which total sea level rose during the 20th century in the North Sea. This means that ocean dynamics would have the potential to double the speed of sea level rise very quickly at the European coast if the CMIP6 models are realistic. It is difficult to assess how realistic these ocean dynamics patterns are because regular measurements of temperature and salinity at depth are only available from the ARGO program since the early 2000s (Riser et al. 2016). At these time scales local steric sea level is largely influenced by natural variability (Calafat, Chambers, and Tsimplis 2012). Due to this variability, we will only be able to constrain this process decades after it has already started. This is the reason why we include this uncertainty prominently in our sea level scenarios.

3 Sea level scenarios

3.1 Method

To obtain future total sea level change, each contributor is projected independently, and all contributors are then added together. The probabilistic sea level projection model is based on the "process-based" IPCC AR5 global projection framework (Church et al. 2013). Note that AR5 used different frameworks for global and regional projections. We refer the reader to previous publications for a complete description of the model: global probabilistic projections were described in Le Bars, Drijfhout, and de Vries (2017) and in Le Bars (2018) while regional projections are described in Haasnoot et al. (2020). The main improvement between our model and the one used by AR5 to make regional projections is that the dependencies between processes arising from a common dependence on GSAT are retained. This is important to have more accurate uncertainty estimates, as mentioned by Palmer et al. (2020). The tradeoff for this higher accuracy is that it makes the model more complicated, which is probably the main reason why it is not widely used. The framework used for the AR6 sea level projections for instance, based on Kopp et al. (2014), assumes that most sea level contributors are independent of each other which underestimates the total uncertainty in most places (Lambert et al. 2021). In probabilistic projections based on CMIP5 a multiplication factor of 1.64 is normally applied to the GSAT and thermosteric sea level ensemble standard deviation to quantify the AR5 expert judgement that the model 5-95 percentiles correspond to the real-world *likely range* (a probability of 66% or more). Given that we use scenarios and that we use CMIP6 instead of CMIP5 we do not apply the multiplication factor here. Some dependences between sea-level contributors directly follow from their common dependence on GSAT but

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this is not the case for the dependence between GSAT and thermosteric sea level. Here we chose to follow AR5, we use a correlation factor of 1 between them.

Projections are obtained following a two-step process. First, global probabilistic sea level projections are computed using a Monte Carlo simulation to randomly sample each sea level contributor (X_x, see Table 2), with Surface Mass Balance (SMB) and dynamics computed separately for the Greenland and Antarctic ice sheets:

$$X_{total}^{global} = X_{thermosteric} + X_{glaciers} + X_{Gsmb} + X_{Gdyn} + X_{Asmb} + X_{Adyn} + X_{LWS}$$

Table 2: Meaning of the sea-level contributors symbols

Symbol	Description	Symbol	Description
$X_{thermosteric}$	Global-mean thermosteric sea-level change	X_{Asmb}	Antarctic Surface Mass Balance
$X_{glaciers}$	Glaciers	X_{Adyn}	Antarctic dynamics
X_{Gsmb}	Greenland Surface Mass Balance	X_{LWS}	Land Water Storage
X_{Gdyn}	Greenland dynamics	X_{Odyn}	Ocean dynamics
		X_{GIA}	Glacial Isostatic Adjustment

To obtain regional sea level, each contributor is then multiplied by a spatial fingerprint that includes the changes in the gravitational field, in the earth rotation speed and axis, and elastic earth's rebound. These fingerprints (called F_x in the equation below) are the same as used in AR5 (Church et al. 2013; Slangen et al. 2014). Two more processes are also added: the ocean dynamic changes, as diagnosed from the CMIP6 models (see section 2), and the vertical land motions which are assumed here to be solely composed of the Glacial Isostatic Adjustment (GIA):

$$X_{total}^{regional} = X_{thermosteric} + F_{glaciers}X_{glaciers} + F_{Gsmb}X_{Gsmb} + \mathrm{F}_{\mathrm{Gdyn}}X_{Gdyn} + F_{Asmb}X_{Asmb} + F_{Adyn}X_{Adyn} + F_{LWS}X_{LWS} + X_{Odyn} + X_{GIA}$$

Now we describe the models used for each contributor. For Greenland SMB (X_{Gsmb}), Greenland dynamics (X_{Gdyn}), Antarctic SMB(X_{Asmb}) and land water storage (X_{LWS}) the models are kept the same as in AR5. Greenland dynamics and land water storage contribution to sea level were assumed to be independent of temperature so the contributions do not change. However, the Greenland and Antarctic SMB are temperature dependent so as we update our temperature forcing from CMIP5 to CMIP6 these contributions also change.

Global-mean thermosteric ($X_{thermosteric}$) and ocean dynamic (X_{Odyn}) are computed from CMIP6 instead of CMIP5 as explained in section 2. The Antarctic dynamics is computed in two different ways depending on the storylines. The AR5 method is used for conservative projections. It is based on a probabilistic extrapolation of discharge observations (Little, Urban, and Oppenheimer 2013) and is assumed to be independent of GSAT and of the emission scenario. For worst case projections we use the linear response functions of an ensemble of 16 ice sheet models computed in the LARMIP-2 project (Levermann et al. 2020). This is an update of the LARMIP project in which only 5 models participated (Levermann et al. 2014). The LARMIP2 results used here are not a priori built for extreme projections but they are found to provide much larger mass loss contributions than projections based on Ice Sheet Model

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Intercomparison for CMIP6 (ISMIP6, Seroussi et al. 2020; Edwards et al. 2021). The reason might be due to the larger basal melt value used to force the ice sheet models in LARMIP2 compared to ISMIP6 (Jourdain et al. 2020). The glacier model is updated according to AR6 (Fox-Kemper et al. 2021). The same parametric fit method as AR5 is used but the 7 GlacierMIP2 models are used instead of the 4 models used in AR5. The contribution from GIA is from the ICE-6G_C model (Peltier, Argus, and Drummond 2015).

The time extension up to 2125 is also performed per contributor. The global surface air temperature (GSAT) used as a forcing for a few components is extrapolated using a second order polynomial fit over the period 1980-2100. This provides the necessary input to extrapolate all contributors that are only forced by GSAT: $X_{glaciers}$, X_{Gsmb}, X_{Asmb}, X_{Adyn}. The $X_{thermosteric}$ and X_{Odyn} are extrapolated in the same way as GSAT. The X_{Gdyn} and X_{LWS} are already modelled as polynomial so they are easily extrapolated. X_{GIA} is assumed to have constant rate over time because its time scale of variation is much longer than a century.

3.2 Scenario choice

Because there is still a large uncertainty around many of the sea level contributors, it is useful to combine the probabilistic model with a scenario approach. For such an approach we replace the probabilistic estimation of some contributors by a choice, or we explicitly choose one method to estimate the probabilities when another one, that would provide different results, would also have been possible. This is equivalent to recognizing that the uncertainty from these contributors is not quantifiable probabilistically, it is a situation of “deep uncertainty” (Lempert, Popper, and Bankes 2003), and is therefore explored through scenarios: What if X, Y and Z happen? The resulting likelihood of such scenarios is not quantified by a probability but by a subjective estimation of how reasonable the choices made in making them are.

The first element for which the uncertainty is not quantified is the emission scenario that humanity will follow. This is a natural choice which is made by all IPCC reports. The second element is the future contribution of Antarctic dynamics. That is also a common choice because it is accepted to be one of the largest sources of uncertainty in global sea level projections (Bamber et al. 2019). We note here that the future amount of Greenland melt is also highly uncertain but since we are interested in future European sea level for which the fingerprint of Greenland is around 0.1 (Slangen et al. 2014), the regional uncertainty from Greenland is 10% of the global one. Note that this is a rough order of magnitude; since Europe is close to Greenland the fingerprint varies very rapidly as one moves away from the ice sheet. It is 0 or even negative for Northern Europe and higher in southern Europe. And it also depends on where in Greenland the mass is lost (Mitrovica et al. 2018). The third element that we use to define our scenarios is ocean dynamics because as discussed in section 2 it is not very well constrained and yet is important for European sea level projections (Vries, Katsman, and Drijfhout 2014). Another complication for this process is that using the CMIP ensembles to make probabilistic projections is possible at one location but not for a region because computing the percentiles for each grid cell and making a map of a given percentile will overestimate the real uncertainty. Because this process has a global mean of 0, this physical property is not fulfilled when treating each grid cell of a map independently. In other words, if ocean dynamics is larger than expected in one region of the world, it will be lower than expected in another one: there is a spatial anti-correlation. Two options are then possible: we can either use the mean of the model ensemble or pick a specific model. We use both options in our storylines.

We present three storylines that will be used to investigate the uncertainty in future impacts on coastal infrastructure of a storm like Xaver or Xynthia if they happened 100 years from now, in 2121. We provide an overview of our three scenarios in Table 3. The choice of the two models used for ocean dynamics is motivated in section 2 (Figure 7).

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Our low scenario, that could also be considered the "best case" for Europe, is defined using the SSP1-2.6 scenario which results in around 2ºC warming above preindustrial in 2100. The Antarctic dynamics is projected using a linear extrapolation of observed discharge (AR5, Little, Urban, and Oppenheimer 2013). The ocean dynamics comes from GISS-E2-1-G which is one of the few models for which this contribution is close to 0. In the end to obtain a single number we choose the 5th percentile of the final probability distribution. This scenario can be used for no regret policy, it is almost certain that sea level will rise more than in this scenario so any adaptation measure for this level will be justified.

For the medium scenario, we use the SSP2-4.5 emission scenario which results in a GSAT increase of 3.4ºC in 2100. Antarctic dynamics is the same as for the low scenario, ocean dynamics is the ensemble mean and the final 50th percentile of the probability distribution is chosen. This is the most neutral choice, that could be called the "median case" about future sea level.

Finally, our high scenario can be seen as a consensual "worst case". Consensual because it still does not include the controversial Marine Ice Cliff Instability (DeConto and Pollard 2016; Bassis et al. 2021) that was shown to result in even faster sea level rise (Le Bars, Drijfhout, and de Vries 2017; Kopp et al. 2017). It uses SSP5-85, the highest emission scenario that results in a warming of 5.6ºC in 2100, the latest linear response functions from ice sheet models that took part to the LARMIP-2 project (Levermann et al. 2020). The UKESM1-0-LL model is used for the ocean dynamics and the 95th percentile of the final probability distribution is selected. It can be used to explore a very extreme future with low probability.

Table 3: Summary of the storylines choices

Scenario names	Emission scenario	Antarctic dynamics	Ocean dynamics	Percentile of final distribution
Low	SSP1-2.6	Little et al. 2013	GISS-E2-1-G	5th
Medium	SSP2-4.5	Little et al. 2013	Ensemble mean	50th
High	SSP5-8.5	(Anders Levermann et al. 2020)	UKESM1-0-LL	95th

3.2.1 Code and data availability

The code to compute the scenarios was written in Python and is available on GitHub under the open source GPLv3 license (https://github.com/dlebars/SLProj). The following open-source libraries were used: Xarray to read and write NetCDF files, numpy and Pandas.

The data is available at Zenodo (10.5281/zenodo.5347691).

3.3 Results

Global maps of total sea level in 2120-2125 are shown for each sea level scenario (Figure 8). Because some of the fingerprints of different contributors to sea level tend to compensate each other the total sea level is more spatially homogeneous than individual contributors. In particular, the large regional differences found for ocean dynamic sea-level change (section 2) are relatively less important when total sea level is considered. Nevertheless, there are still some large spatial differences, for instance in the "low" scenario the Arctic has more sea level rise than average because the rise due to ocean dynamics outweighs the drop from Greenland and Arctic glaciers. In contrast, in the "high" scenario the coasts of Greenland and West Antarctica really stand out as having a large drop in sea level of 1 to 2 meters while the rest of the world sees a sea level rise of more than 2 meters.

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Total sea-level rise at the European coast is also more homogeneous than ocean dynamic sea-level rise (Figure 9). The North/South gradient in ocean dynamics is compensated by the Greenland fingerprint. Northern Europe being closer to Greenland and Arctic glaciers, sea level is less sensitive to these sources than the coasts of Southern Europe.

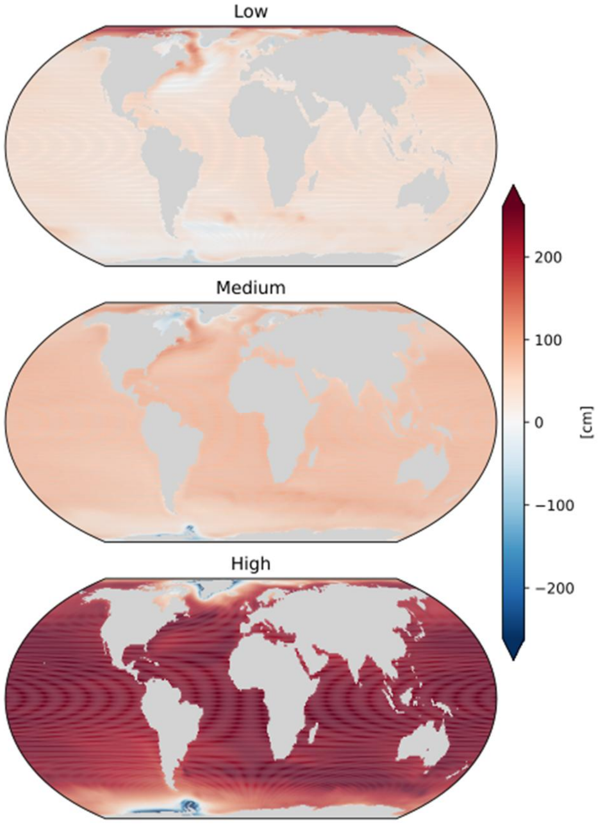

Figure 8: Total sea level in 2120-2125 compared to the reference period 1986-2005 for the three scenarios developed in this report (Table 3).

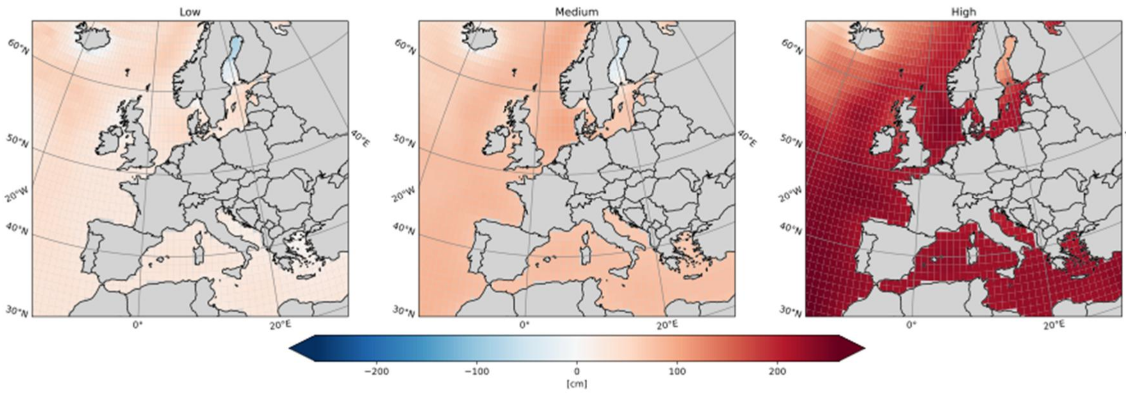

Figure 9: Same field as the previous figure but zoomed in on Europe.

We also show some time series for the coast of Northern Germany that will be used for the Xaver storm surge storyline. The relative importance of the different contributors is very different depending on the scenario (Figure 10). For the “low” scenario ocean stero-dynamics (global thermosteric and ocean dynamics together), GIA and glaciers have the largest impact on total sea level. However, for the “high” scenario Antarctic dynamics and ocean stero-dynamics are almost the only contributors that matter. This is because glaciers have a limited

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potential to contribute to global-mean sea-level rise, around 40 cm (Huss and Farinotti 2012), GIA is independent on climate change and Greenland's fingerprint is very small at that location (Slangen et al. 2014). This is also visible in Figure 11 where the three scenarios are compared with each other for each sea-level contributor.

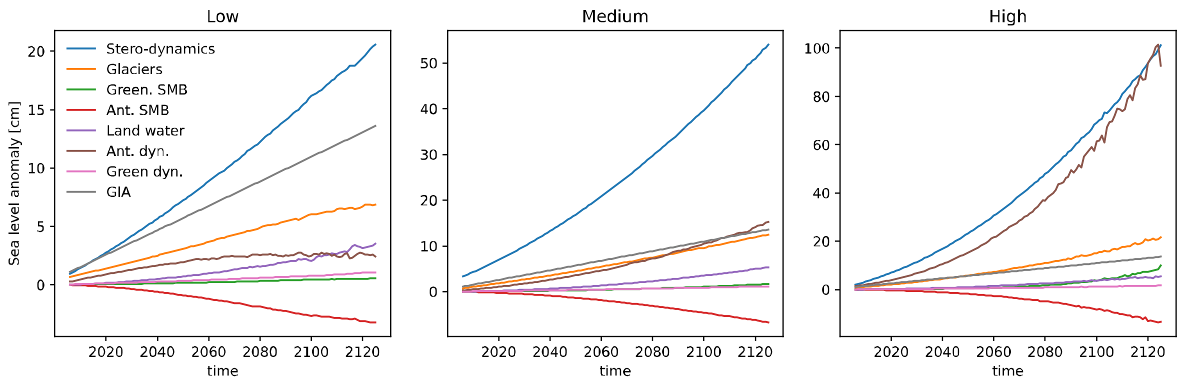

Figure 10: Time series of sea level contributors for the North Sea coast of Northern Germany for the three scenarios. Stero-dynamics is the sum of global-mean thermosteric sea-level rise and ocean dynamics. Total sea level per scenario is shown in Figure 11 (last panel)

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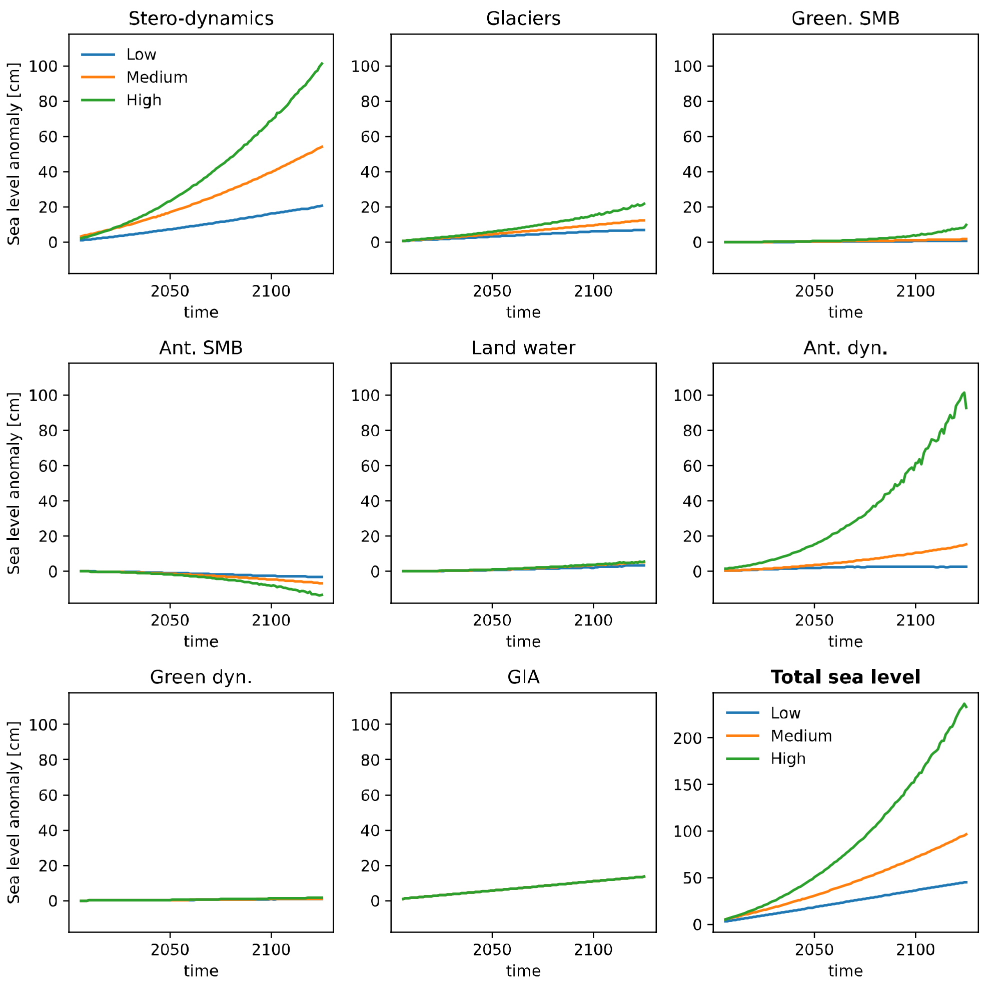

Figure 11: Comparison of scenario for each sea level contributor and for the total sea level (lower right panel). Note that total sea level is shown with different y-axis values than the other panels. Stero-dynamics is the sum of global-mean thermosteric sea-level rise and ocean dynamics.

3.4 Discussion

Providing sea-level projections up to 2125 instead of the usual 2100 or 2300 (Pörtner et al. 2019) provides a different perspective on the importance of different contributors and on the importance of choices made when designing the scenarios. The divergence between scenarios accelerates over time and becomes greater after 2100.

The three scenarios provided here are examples of how our sea-level projection model can be used to explore the future. We provide yearly averaged global fields for these scenarios, but they are especially designed to study the future impact of the storm Xaver and Xynthia within WP7 of RECEIPT. Different scenarios, with for example different choices about Marine Ice Cliff Instability, vertical land motion or the emission scenario can be made for other regions of the word in a co-creation process with other partners from RECEIPT or external stakeholders.

We do not address in this report the use of observations to constrain or evaluate future sea level because as discussed in section 2 for dynamics that is not straightforward (Wang et al. 2021). However, as sea level budgets improve this could become more common in the future (Frederikse et al. 2020).

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4 Arctic sea ice scenarios

Future sea ice scenarios are easier to make than future sea level because sea ice is a variable of climate models that can directly be compared to observations. While CMIP3 and CMIP5 model ensembles underestimated the fast retreat of Arctic sea ice over the observational period (Stroeve et al. 2012), Arctic sea ice in CMIP6 models is more sensitive to global warming, in accordance with observations (Notz and Community 2020). Sea ice projections from CMIP6 models are freely available and have already been used in the context of potential change in shipping lanes through the Arctic by Li et al. 2021. Therefore, we recommend that if in the future we would like to investigate the future disruptions of the opening of Arctic shipping routes on the European coastal infrastructure the data from Li et al. 2021 can be used.

5 Conclusion

In this report, we describe a method to compute global-mean thermosteric and ocean dynamic sea level from CMIP5 and CMIP6 ensembles. We show that for both these variables the model divergence in projecting the 21st century has increased between CMIP5 and CMIP6. While the median thermosteric sea level didn't increase a lot (~1 to 2 cm) the projection of ocean dynamics in the North Sea almost doubled for the RCP4.5-SSP2-4.5 scenario (and other scenarios, not shown here). We provided some explanation for this difference. Thermosteric sea level mostly reacts to the time integrated GSAT while ocean dynamics is linked to GSAT itself.

We presented three very diverse sea level scenarios that will be used for the storylines of RECEIPT WP7 to investigate the impact of recent storms if they were to impact Europe in 100 years from now under different levels of sea level rise. The method to design the scenarios is based on a probabilistic projection but it uses a few non-probabilistic choices to account for the deep uncertainty associated with future sea level. The emission scenario, the model of Antarctic dynamics and ocean dynamics are chosen because they are the most relevant to the European coast.

The method developed here to design sea level scenarios is very flexible and can be adapted to the needs of many stakeholders in Europe or elsewhere.

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7 Appendices

Table 4: Information about CMIP6 Models used for the historical and piControl experiments for the zos variable. The information about models used for the future scenarios and for CMIP5 is provided as .csv files in supplementary material.

Center	Model	historical_ Variant	Grid	historical_ Version	piControl_ Variant	piControl_ Version
CSIRO-ARCCSS	ACCESS-CM2	r1i1p1f1	gn	v20191108	r1i1p1f1	v20191112
CSIRO	ACCESS-ESM1-5	r1i1p1f1	gn	v20191115	r1i1p1f1	v20191214
AWI	AWI-CM-1-1-MR	r1i1p1f1	gn	v20181218	r1i1p1f1	v20181218
AWI	AWI-ESM-1-1-LR	r1i1p1f1	gn	v20200212	r1i1p1f1	v20200212
BCC	BCC-CSM2-MR	r1i1p1f1	gn	v20190429	r1i1p1f1	v20181015
BCC	BCC-ESM1	r1i1p1f1	gn	v20181129	r1i1p1f1	v20181218

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CAMS	CAMS-CSM1-0	r1i1p1f1	gn	v20190708	r1i1p1f1	v20190729
CAS	CAS-ESM2-0	r1i1p1f1	gn	v20200306	r1i1p1f1	v20200307
NCAR	CESM2	r1i1p1f1	gr	v20190308	r1i1p1f1	v20190320
NCAR	CESM2-FV2	r1i1p1f1	gr	v20191120	r1i1p1f1	v20191120
NCAR	CESM2-WACCM	r1i1p1f1	gr	v20190808	r1i1p1f1	v20190320
NCAR	CESM2-WACCM-FV2	r1i1p1f1	gr	v20191120	r1i1p1f1	v20191120
THU	CIESM	r1i1p1f1	gn	v20200220	r1i1p1f1	v20200220
CMCC	CMCC-CM2-SR5	r1i1p1f1	gn	v20200616	r1i1p1f1	v20200616
CNRM-CERFACS	CNRM-CM6-1	r1i1p1f2	gn	v20180917	r1i1p1f2	v20180814
CNRM-CERFACS	CNRM-CM6-1-HR	r1i1p1f2	gn	v20191021	r1i1p1f2	v20191021
CNRM-CERFACS	CNRM-ESM2-1	r1i1p1f2	gn	v20181206	r1i1p1f2	v20181115
CCCma	CanESM5	r1i1p1f1	gn	v20190429	r1i1p1f1	v20190429
CCCma	CanESM5-CanOE	r1i1p2f1	gn	v20190429	r1i1p2f1	v20190429
E3SM-Project	E3SM-1-0	r1i1p1f1	gr	v20190826	r1i1p1f1	v20191007
E3SM-Project	E3SM-1-1	r1i1p1f1	gr	v20191204	r1i1p1f1	v20191028
E3SM-Project	E3SM-1-1-ECA	r1i1p1f1	gr	v20200127	r1i1p1f1	v20200128
EC-Earth-Consortium	EC-Earth3	r1i1p1f1	gn	v20200310	r1i1p1f1	v20200312

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EC-Earth-Consortium	EC-Earth3-Veg	r1i1p1f1	gn	v20200225	r1i1p1f1	v20200226
EC-Earth-Consortium	EC-Earth3-Veg-LR	r1i1p1f1	gn	v20200217	r1i1p1f1	v20200213
CAS	FGOALS-f3-L	r1i1p1f1	gn	v20191007	r1i1p1f1	v20191028
CAS	FGOALS-g3	r1i1p1f1	gn	v20191106	r1i1p1f1	v20191125
NOAA-GFDL	GFDL-CM4	r1i1p1f1	gr	v20180701	r1i1p1f1	v20180701
NASA-GISS	GISS-E2-1-G	r1i1p1f1	gn	v20180827	r1i1p1f1	v20180824
NASA-GISS	GISS-E2-1-G-CC	r1i1p1f1	gn	v20190815	r1i1p1f1	v20190815
NASA-GISS	GISS-E2-1-H	r1i1p1f1	gr	v20190403	r1i1p1f1	v20190410
MOHC	HadGEM3-GC31-LL	r1i1p1f3	gn	v20190624	r1i1p1f1	v20190628
MOHC	HadGEM3-GC31-MM	r1i1p1f3	gn	v20191207	r1i1p1f1	v20191204
INM	INM-CM4-8	r1i1p1f1	gr1	v20190530	r1i1p1f1	v20190605
INM	INM-CM5-0	r1i1p1f1	gr1	v20190610	r1i1p1f1	v20190619
IPSL	IPSL-CM6A-LR	r1i1p1f1	gn	v20180803	r1i1p1f1	v20200326
MIROC	MIROC-ES2L	r1i1p1f2	gr1	v20200731	r1i1p1f2	v20200731
MIROC	MIROC6	r1i1p1f1	gn	v20181212	r1i1p1f1	v20181212
HAMMOZ-Consortium	MPI-ESM-1-2-HAM	r1i1p1f1	gn	v20190627	r1i1p1f1	v20190627

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MPI-M	MPI-ESM1-2-HR	r1i1p1f1	gn	v20190710	r1i1p1f1	v20190710
MPI-M	MPI-ESM1-2-LR	r1i1p1f1	gn	v20190710	r1i1p1f1	v20190710
MRI	MRI-ESM2-0	r1i1p1f1	gr	v20191205	r1i1p1f1	v20191224
NUIST	NESM3	r1i1p1f1	gn	v20190703	r1i1p1f1	v20190704
NCC	NorCPM1	r1i1p1f1	gn	v20190914	r1i1p1f1	v20190914
NCC	NorESM2-LM	r1i1p1f1	gn	v20190815	r1i1p1f1	v20190920
NCC	NorESM2-MM	r1i1p1f1	gn	v20191108	r1i1p1f1	v20191108
SNU	SAM0-UNICON	r1i1p1f1	gn	v20190323	r1i1p1f1	v20190910
MOHC	UKESM1-0-LL	r1i1p1f2	gn	v20190627	r1i1p1f2	v20190827

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