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Projecting Future Sea Level Rise

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POSTbriefs are responsive policy briefings from the Parliamentary Office of Science and Technology based on mini literature reviews and peer review.

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Summary

This POSTbrief complements POSTnote 555 on Rising Sea Levels, which sets out the causes, likely future levels and implications of sea level rise. This POSTbrief provides further information on current projections of future sea level rise. It introduces sea level rise projections and discusses the various future emission scenarios used in the projections, the different modelling methods employed, as well as the likelihood ranges and uncertainties associated with them. It also provides an overview of the current sea level rise projections arising from different modelling techniques and emission scenarios and discusses high-end sea level rise scenarios.

List of Acronyms

- **AR5** Fifth Assessment Report (of IPCC)
- **AR6** Sixth Assessment Report (of IPCC)
- **CO_2** Carbon Dioxide
- **CMIP** Coupled Model Intercomparison Project
- **GHG** Greenhouse Gas
- **GMSL** Global Mean Sea Level
- **H++** "High-Plus-Plus" Scenario (in UKCP)
- **IAM** Integrated Assessment Model
- **IPCC** Intergovernmental Panel on Climate Change
- **NOAA** National Oceanic and Atmospheric Administration (in the USA)
- **PBM** Process-Based Model
- **RCP** Representative Concentration Pathway
- **RF** Radiative Forcing
- **RSL** Relative Sea Level (Sea level relative to the Earth's crust, accounting for vertical land movement)
- **SEM** Semi-Empirical Model
- **UKCP** UK Climate Projections (Met Office)

Sea Level Rise Projections

It is impossible to predict future sea level rise exactly, but computer models can provide projections of likely future changes. These projections are based on different modelling approaches and different possible future trajectories of atmospheric greenhouse gas (GHG) concentrations and global surface temperature changes. The Intergovernmental Panel on Climate Change (IPCC) produces assessment reports every 6-8 years that draw on the available peer-reviewed scientific literature to provide projections of sea level rise (and other climatic changes) up to 2100 and beyond, and assess confidence in the evidence. The most recent IPCC Fifth Assessment Report (AR5) was published in 2013-14, and the upcoming Sixth Assessment Report (AR6) is due in 2020-21.

Future Emission Scenarios

Sea level rise projections are developed for a set of four different Representative Concentration Pathways (RCPs), which represent possible 21st century trajectories of atmospheric concentrations of GHGs such as carbon dioxide (CO_2).[1] RCPs are defined by their approximate total radiative forcing (RF) in the year 2100, relative to 1750 (pre-industrial).

Radiative forcing is a complex process involving interactions within the Earth's atmosphere.[2] Positive RF leads to surface warming while negative RF leads to surface cooling. Higher atmospheric GHG concentrations result in a higher RF. Table 1 provides an overview of the RCPs and their associated atmospheric CO_2 concentration by 2100 as prescribed in model simulations alongside their associated radiative forcing value.[3] For reference, in 2016 the mean atmospheric CO_2 concentration was 400 parts per million (ppm), and it is currently rising at around 2 ppm per year.[4]

RCP	Model prescribed CO_2 concentration by 2100	Approximate Radiative Forcing in 2100, relative to 1750
RCP2.6	421 parts per million (ppm)	2.6 Watts per square metre (W/m^2)
RCP4.5	538 ppm	4.5 W/m^2
RCP6.0	670 ppm	6.0 W/m^2
RCP8.5	936 ppm	8.5 W/m^2

Table 1: Representative Concentration Pathways (RCPs) with approximate CO_2 concentrations and radiative forcing by 2100.

1 Van Vuuren et al., 2011. The Representative Concentration Pathways: an Overview. Climate Change.
2 Knutti & Hegerl, 2008. The Equilibrium Sensitivity of the Earth's Temperature to Radiation Changes. Nature Geoscience.
3 IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
4 NASA, 2017. Carbon Dioxide. Global Climate Change: Vital Signs.

The IPCC AR5 projects a greater than 66% likelihood that by 2100 global surface temperature increase will exceed 1.5°C (relative to pre-industrial temperatures) for all RCP scenarios except RCP2.6, and will exceed 2°C for RCP6.0 and RCP8.5. It further projects a greater than 50% likelihood that it will also exceed 2°C for RCP4.5.[3] Figure 1 shows how these projections of global surface temperature change correlate with projected changes in radiative forcing, for each of the RCPs.

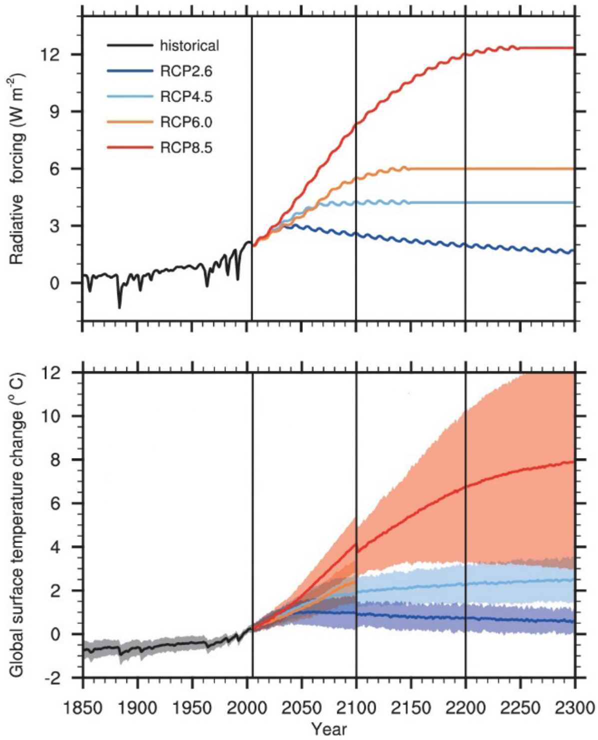

Figure 1: IPCC projections of radiative forcing (top) and global surface temperature change (bottom) for each RCP. Solid lines indicate the multi-model mean and shaded areas represent the 90% confidence intervals. Discontinuities at 2100 are due to a different number of models being used to calculate projections beyond 2100. RCP4.5 and RCP6.0 are combined as one scenario for temperature projections beyond 2100.[5]

Future atmospheric GHG concentrations depend on future rates of GHG emission into the atmosphere. Therefore, each RCP has an associated 21st century GHG emissions trajectory:

- RCP2.6 describes a scenario of large scale mitigation action, where GHG emissions peak during the 2020s and then decline, with net CO_2 emissions reduced to zero by 2080. RCP2.6 is referred to as the "Low" emission scenario in the Met Office UK Climate Projections (UKCP).
- RCP4.5 and RCP6.0 represent mid-range mitigation scenarios with GHG emissions stabilizing and declining later in the 21st century. In UKCP, these trajectories are combined into a single "Medium" emission scenario.
- RCP8.5 assumes more or less unabated GHG emissions throughout the 21st century. This is the "High" emission scenario in UKCP.

5 Stocker et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis.* Contribution of WG1 to the IPCC Fifth Assessment Report.

The RCPs are used by climate modellers to conduct climate model experiments and make projections of future changes, such as for sea level rise. At the same time, Integrated Assessment Models (IAMs) explore a range of different technological, socio-economic and policy futures that could lead to a particular RCP. POSTnote 549 on GHG Removal provides further information on IAMs.

Modelling Methods

There are two main modelling methods used in the scientific literature for projections of future sea level rise: process-based models (PBMs), and semi-empirical models (SEMs). There is also a third technique using what are termed 'simple climate models'. The IPCC AR5 considered both PBM and SEM results and made an assessment of 'low confidence' in SEM projections, due to limited evidence and consensus within the scientific community about the reliability of this method. The IPCC AR5 assigned greater confidence to process-based projections, and therefore based its sea level rise projections on PBM results.[6]

Process-Based Models

Process-based models use physical laws to model the individual physical mechanisms that contribute to sea level rise (see POSTnote 555). Projections into the future are then based on the sum of these modelled contributions. PBMs are rooted in state-of-the-art climate model simulations which represent the forefront of the current scientific ability to simulate the global weather and climate system. They are similar in basic structure to the models used in everyday weather forecasting. The Coupled Model Intercomparison Project (CMIP) provides a global framework for scientists to compare and validate the output from different PBMs.[7] The IPCC AR5 projections are based on 21 PBMs from phase 5 of CMIP (CMIP5).[6]

Semi-Empirical Models

Semi-empirical models are statistical models that describe changes in sea level as an integrated response of the entire climate system, but do not model the individual components contributing to sea level rise. They use relationships between observations of past changes in sea level and other climatic changes, e.g. changes in temperature or radiative forcing, to make future projections.[8] At the time of the IPCC AR5, most SEM sea level rise projections were substantially higher than process-based projections, and there was low confidence in physical explanations for this, leading to the IPCC's assessment of low confidence in SEM projections.[6] More recent SEM projections since the

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6 Church et al., 2013. Sea Level Change. In: *Climate Change 2013: The Physical Science Basis*. Contribution of WG1 to the IPCC Fifth Assessment Report.

7 Meehl et al., 2000. The Coupled Model Intercomparison Project (CMIP). Bulletin of the American Meteorological Society.

8 Rahmstorf, 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. Science

IPCC AR5 are lower and have converged with the PBM results,[9,10] but there is still low confidence in the SEMs and the resulting projections within the scientific community.[11]

Simple Climate Models

Simple climate models, like process-based models, are rooted in a physical description of the climate system, but at a much coarser resolution. They are therefore quicker and cheaper to run than PBMs, for a wider range of climate change scenarios. The recent MAGICC model is an example of a simple climate model, which uses physical limits from CMIP5 models to constrain the processes that contribute to sea level rise.[12]

Overview of Projections

The IPCC AR5 uses a calibrated uncertainty language, for example a *likely* range means there is a probability of at least 66% that the outcome will lie within the specified range, and a *very likely* range means a probability of at least 90%. For its projections of global mean sea level (GMSL) rise by 2100, the IPCC AR5 assigned a *likely* range. The IPCC AR5 did not assign a *very likely* range, mainly due to uncertainties in the future rate of the Antarctic ice sheet contribution. Sea level rise projections are only meaningful when considered together with their likelihood.

Table 2 provides an overview of recent projections of GMSL rise by 2100 for each of the RCPs, based on the three modelling methods discussed above: 1) the IPCC AR5 process-based projections, 2) a recent SEM study and 3) the MAGICC simple climate model. The IPCC and MAGICC projections are for the *likely* range, the SEM projections are assigned a *very likely* range. The SEM *very likely* range is largely similar to the IPCC *likely* range, except for the higher upper bound of 131 cm of GMSL rise for RCP8.5. This is a result of the wider range of possible outcomes covered by the *very likely* range.

RCP	IPCC AR5, 2013,[6] Process-Based, 66% *likely* range	Mengel et al., 2016,[10] Semi-Empirical, 90% *very likely* range	Nauels et al., 2016,[12] MAGICC model, 66% *likely* range
RCP2.6	28-61 cm	28-56 cm	38-59 cm
RCP4.5	36-71 cm	37-77 cm	48-68 cm
RCP6.0	38-73 cm	N/A	48-72 cm
RCP8.5	52-98 cm	57-131 cm	67-97 cm

Table 2: Projections of GMSL rise by 2100 calculated using three different modelling methods.

9 Kopp et al., 2016. Temperature-Driven Global Sea-level Variability in the Common Era. Proceedings of the National Academy of Sciences.

10 Mengel et al., 2016. Future Sea Level Rise Constrained by Observations and Long-Term Commitment. Proceedings of the National Academy of Sciences.

11 Clark et al., 2015. Recent Progress in Understanding and Projecting Regional and Global Mean Sea Level Change. Current Climate Change Reports.

12 Nauels et al., 2016. Synthesizing Long-Term Sea Level Rise Projections - the MAGICC Sea Level Model. Geoscientific Model Development Discussions.

Some have misinterpreted the upper bound of the IPCC AR5 *likely* range (98 cm of GMSL rise by 2100 for RCP8.5) as a 'worst case scenario' or 'upper limit' to GMSL rise by 2100.[13] There may be situations where the possibility of higher GMSL rise, above the *likely* range, needs to be taken into account. For example, this is the approach taken for the protection of London and the Thames Estuary floodplain from sea level rise (see POSTnote 555, Box 1). Because the extreme upper end of sea level rise projections cannot be modelled accurately, a method called 'expert elicitation' is often employed, i.e. an estimate based on combining the educated guesses of a panel of experts. Using this method, some studies have projected 95%, 99%, or 99.9% likelihood ranges with GMSL rise up to 1.8-2.5 m by 2100.[14,15,16,17,18,19] However, IPCC authors have expressed low confidence in projections relying on expert elicitation, because the respondents are not asked to justify their opinions. They also argue that the current level of scientific understanding does not allow for reliable projections beyond the *likely* range to be made.[11]

Uncertainties and High-End Scenarios

As a caveat to its GMSL projections, the IPCC AR5 stated that:

"Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet (see POSTnote 555), if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is medium confidence (about 5 out of 10 chance) that it would not exceed several tenths of a metre of sea level rise during the 21st century."[6]

The same caveat holds for SEM projections, as they rely on relationships between GMSL and other climatic changes during past observational periods, which cannot account for processes such as ice sheet instability that did not occur during that observational period.

As indicated in POSTnote 555, several studies since the IPCC AR5 have suggested that a collapse of marine-based sectors of the Antarctic ice sheet may already be underway in West Antarctica.[20,21,22] Quantifying this potential

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13 Church et al., 2013a. Sea Level Rise by 2100. Science
14 Kopp et al, 2014. Probabilistic 21st and 22nd Century Sea-Level Projections at a Global Network of Tide-Gauge Sites. Earth's Future.
15 Horton et al., 2014. Expert Assessment of Sea-Level Rise by AD 2100 and AD 2300. Quaternary Science Reviews.
16 Jevrejeva et al., 2014. Upper Limit for Sea Level Projections by 2100. Environmental Research Letters.
17 Grinsted et al., 2015. Sea Level Rise Projections for Northern Europe under RCP8.5. Climate Research.
18 Jackson and Jevrejeva, 2016. A Probabilistic Approach to 21st Century Regional Sea-Level Projections using RCP and High-End Scenarios. Global and Planetary Change.
19 Jevrejeva et al., 2016. Coastal Sea Level Rise with Warming Above 2°C. Proceedings of the National Academy of Sciences.
20 Favier et al, 2014. Retreat of Pine Island Glacier Controlled by Marine Ice-Sheet Instability. Nature Climate Change.
21 Joughin et al, 2014. Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. Science.
22 Rignot et al, 2014. Widespread, Rapid Grounding Line Retreat of Pine Island, Thwaites, Smith and Kohler Glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters.

additional Antarctic contribution currently presents the largest source of uncertainty in future sea level rise projections. Two modelling studies have projected an additional Antarctic contribution of up to 20-30 cm of GMSL rise by 2100, in line with the IPCC's "several tenths of a metre".[23,24] However, it has also been suggested that an additional contribution of more than 1 m by 2100 is possible through processes of ice shelf fracturing, triggering rapid ice cliff collapse,[25] although this "ice cliff instability" is yet to be observed.

To account for the different projections, likelihood ranges and the uncertainty about the additional Antarctic contribution, some high-risk, low-probability scenarios of sea level rise by 2100 have been developed. These are aimed to aid users in contingency planning when a high level of protection is required.[26] Such scenarios lie beyond the *likely* and *very likely* ranges, but cannot be ruled out. In the Met Office UKCP from 2009, published prior to the IPCC AR5, a "High-plus-plus" (H++) scenario was included with associated relative sea level (RSL) rise for the UK of up to 1.9 m by 2100.[27] The upcoming revised UKCP, due to be published in 2018, will report on a new H++ scenario for 21st century sea level rise as part of ongoing work in collaboration with the UK and wider research community. Similarly, the US National Oceanic and Atmospheric Administration (NOAA), recently revised their "Extreme" scenario of GMSL rise by 2100 from 2.0 m up to 2.5 m.[28] The UK Government Office of Science has commissioned an evidence review on "Current and Future Impacts of Sea Level Rise on the UK", due to be published later in 2017, as part of their "Foresight, Future of the Sea" project. The report summarises current research into UK impacts of different sea level rise projections, including an "Extreme" scenario of up to 2.5 m of GMSL rise by 2100.[29]

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23 Cornford et al., 2015. Century-Scale Simulations of the Response of the West Antarctic Ice Sheet to a Warming Climate. The Cryosphere.
24 Ritz et al., 2015. Potential Sea-Level Rise from Antarctic Ice-Sheet Instability Constrained by Observations. Nature.
25 DeConto and Pollard, 2016. Contribution of Antarctica to Past and Future Sea-Level Rise. Nature.
26 Hinkel et al., 2015. Sea-Level Rise Scenarios and Coastal Risk Management. Nature Climate Change
27 Lowe et al., 2009. UK Climate Projections Science Report: Marine and Coastal Projections. Met Office Hadley Centre, Exeter, UK.
28 Sweet et al., 2017. Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083.
29 Edwards, 2017 (In Review). Current and Future Impacts of Sea Level Rise on the UK. Government Office of Science, "Foresight, Future of the Sea" Evidence Review.