Cambridge Prisms: Coastal Futures

www.cambridge.org/cft

Review

Cite this article: Slangen ABA, Palmer MD, Camargo CML, Church JA, Edwards TL, Hermans THJ, Hewitt HT, Garner GG, Gregory JM, Kopp RE, Santos VM and van de Wal RSW (2023). The evolution of 21st century sea-level projections from IPCC AR5 to AR6 and beyond. *Cambridge Prisms: Coastal Futures*, **1**, e7, 1–13
https://doi.org/10.1017/cft.2022.8

Received: 22 July 2022
Revised: 28 November 2022
Accepted: 03 December 2022

Keywords:
Sea-level changes; Numerical modelling; Climate change; Coastal change

Authors for correspondence:
Aimée B.A. Slangen and Matthew D. Palmer,
Email: aimee.slangen@nioz.nl;
matthew.palmer@metoffice.gov.uk

The evolution of 21st century sea-level projections from IPCC AR5 to AR6 and beyond

Aimée B.A. Slangen[1], Matthew D. Palmer[2,3], Carolina M.L. Camargo[1,4], John A. Church[5], Tamsin L. Edwards[6], Tim H.J. Hermans[1,4,7], Helene T. Hewitt[2], Gregory G. Garner[8], Jonathan M. Gregory[2,9], Robert E. Kopp[8], Victor Malagon Santos[1] and Roderik S.W. van de Wal[7,10]

[1]Department of Estuarine and Delta Systems, NIOZ Royal Netherlands Institute for Sea Research, Yerseke, The Netherlands; [2]Met Office Hadley Centre, Exeter, UK; [3]School of Earth Sciences, University of Bristol, Bristol, UK; [4]Department of Geoscience and Remote Sensing, TU Delft, Delft, The Netherlands; [5]Climate Change Research Centre, University of New South Wales, Sydney, NSW, Australia; [6]Department of Geography, King's College London, London, UK; [7]Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, The Netherlands; [8]Department of Earth and Planetary Sciences and Rutgers Institute of Earth, Ocean, and Atmospheric Sciences, Rutgers University, New Brunswick, NJ, USA; [9]National Centre for Atmospheric Science, University of Reading, Reading, UK and [10]Faculty of Geosciences, Department of Physical Geography, Utrecht University, Utrecht, The Netherlands

Abstract

Sea-level science has seen many recent developments in observations and modelling of the different contributions and the total mean sea-level change. In this overview, we discuss (1) the evolution of the Intergovernmental Panel on Climate Change (IPCC) projections, (2) how the projections compare to observations and (3) the outlook for further improving projections. We start by discussing how the model projections of 21st century sea-level change have changed from the IPCC AR5 report (2013) to SROCC (2019) and AR6 (2021), highlighting similarities and differences in the methodologies and comparing the global mean and regional projections. This shows that there is good agreement in the median values, but also highlights some differences. In addition, we discuss how the different reports included high-end projections. We then show how the AR5 projections (from 2007 onwards) compare against the observations and find that they are highly consistent with each other. Finally, we discuss how to further improve sea-level projections using high-resolution ocean modelling and recent vertical land motion estimates.

Impact statement

Sea-level rise is an important aspect of climate change, with potentially large consequences for coastal communities around the world. Sea-level change is therefore an active area of research that has seen many developments in the past decades. Based on the available research, the Intergovernmental Panel on Climate Change (IPCC) provides regular updates on sea-level projections which are used by policymakers and for adaptation planning. In this review, we compare the sea-level projections from different IPCC reports in the past 10 years and explain what has changed in the methods used and in the numbers presented. We also compare observed changes from the 2021 IPCC report to projected changes from the 2013 IPCC report, for the overlapping period 2007–2018, and find that they are highly consistent. Finally, we share some potential future research directions on improving sea-level projections.

Introduction

Present-day sea-level change (SLC) is primarily a consequence of human-induced climate change, which will impact people and communities all over the world. From a decision-making perspective, knowing how much the sea level will rise, and when, can help to decide which protective measures need to be taken at which point in time. Therefore, sea-level projections are among the most anticipated outcomes of the Intergovernmental Panel on Climate Change (IPCC) assessment reports (ARs). While sea-level extremes are also an important consideration for future coastal hazards, in this review we focus our attention on projections of mean sea level.

In the past 15 years, process-based sea-level projections (i.e., projections which use models to simulate the physical processes and interactions contributing to sea-level change) in the IPCC reports have developed from global-mean only (AR4, Meehl et al., 2007) to regional projections (AR5, Church et al., 2013a). More recent reports focused on the Antarctic contribution (Special Report on Oceans and Cryosphere in a Changing Climate SROCC, Oppenheimer et al., 2019), and provided projections consistent with the assessed Equilibrium Climate Sensitivity (ECS)

(AR6, Fox-Kemper et al., 2021a). The research community has dedicated significant research effort and published many papers on improving the understanding and modelling of the different contributions to SLC, such as ice sheets, glaciers and sterodynamic changes (e.g., Gregory et al., 2016; Nowicki et al., 2016; The IMBIE Team, 2018, 2019; Hock et al., 2019). Since AR5, new global mean and regional projections have been published, using various methods: for instance based on fully coupled climate models (Slangen et al., 2012; Kopp et al., 2014; Slangen et al., 2014a; Carson et al., 2015; Jackson and Jevrejeva, 2016; Buchanan et al., 2017; Palmer et al., 2020), reduced-complexity models (Perrette et al., 2013; Schleussner et al., 2016; Nauels et al., 2017), semi-empirical models (Kopp et al., 2016; Mengel et al., 2016; Bakker et al., 2017; Bittermann et al., 2017; Goodwin et al., 2017; Wong et al., 2017; Jackson et al., 2018; Jevrejeva et al., 2018), structured expert judgement (SEJ) (Bamber et al., 2019), or a mixture of methods (Grinsted et al., 2015; Kopp et al., 2017; Le Bars et al., 2017; Le Cozannet et al., 2017a). There have also been a number of reviews, including a database of sea-level projections (Garner et al., 2018), reviews on developments following AR5 (Clark et al., 2015; Slangen et al., 2017a), overviews of processes and timescales (Horton et al., 2018a; Hamlington et al., 2020), reviews on coastal sea-level change (e.g., Van de Wal et al., 2019) and reviews integrating risk and adaptation assessments (e.g., Nicholls et al., 2021).

One thing that all sea-level projections have in common, despite the different approaches and methodologies, is an uncertainty that grows substantially through time. The uncertainties in regional sea-level projections over the coming years to decades result primarily from internal climate variability (see e.g., Palmer et al., 2020, their Figure 11). On decadal to centennial timescales, uncertainties depend on the future forcings (such as greenhouse gas emissions) and the response of the climate system; and on the modelling uncertainty associated with simulating the different contributions to SLC. The forcing uncertainty can be assessed using different emissions or radiative forcing scenarios, varying from scenarios with net-zero CO_2 emissions by 2050 to scenarios with a tripling of the present-day CO_2 emissions by 2100. The modelling uncertainty can be relatively well quantified for some contributions, such as global mean thermal expansion. For other contributions, such as (multi)-century timescale ice mass loss of the Antarctic Ice Sheet, the uncertainty is characterised as 'deep uncertainty', which means that experts do not know or cannot agree on appropriate conceptual models or the probability distributions used (Lempert et al., 2003; Kopp et al., 2022). These contributions are therefore a topic of much research and debate (e.g., Oppenheimer et al., 2019).

In addition to studies on future sea-level projections, much research has been focused on understanding past observations. A lot of progress has been made in the closing of the sea-level budget for the 20th century, which compares the sum of the observed contributions to the total observed changes, on global (e.g., Gregory et al., 2013; Chambers et al., 2016; Cazenave et al., 2018; Frederikse et al., 2020) and basin scales (e.g., Slangen et al., 2014b; Frederikse et al., 2016; Rietbroek et al., 2016; Frederikse et al., 2018; Wang et al., 2021b). These budget studies have led to important advances in the understanding of sea-level change and its contributing processes on global and regional scales. In addition, the observations can be compared with model simulations (Church et al., 2013c; Meyssignac et al., 2017; Slangen et al., 2017b; Oppenheimer et al., 2019) to test, understand and improve the model representation of the different processes. This has turned out to be challenging, especially for the earlier part of the 20th century: SROCC stated that only 51% of the 1901–1990 observed global mean sea-level (GMSL) change could be explained by models, due to 'the inability of climate models to reproduce some observed regional changes', in particular before 1970. The agreement between models and observations increased to 91% for 1971–2015 and 99% for 2006–2015 (Oppenheimer et al., 2019).

It is also possible to evaluate past projections against observations that have been made since. For instance, for total SLC, Wang et al. (2021a) found an almost identical GMSL trend in the observations and AR5 projections for the period 2007–2018. Lyu et al. (2021) compared observations and climate model output of ocean warming for the purpose of constraining projections. They found a high correlation for the Argo period (2005–2019) and concluded that the observational record over this period is currently the most useful constraint for projections of ocean warming. Such evaluations against the already realised SLC are important to provide further insights and build confidence in sea-level projections.

Here, we will first discuss 'how we got here': recent methodological developments in process-based sea-level projections for the 21st century, with a brief recap of the IPCC sea-level projection methods up to IPCC AR5, followed by a discussion of the key differences between AR5, SROCC and AR6 projections (section 'Key advances in sea-level projections up to IPCC AR6'). Next, we discuss 'where we are', by evaluating AR5 projections of SLC (which start from 2007 onwards) against observational time series (up to 2018), both for total GMSL and for individual contributions (section 'Comparison of the AR5 model simulations with observations'). Finally, we discuss 'where we're going': how can sea-level projections be better tailored for coastal information (section 'Moving towards local information'). Throughout this review, we adopt the sea-level terminology defined by Gregory et al. (2019) and we refer to Box 9.1 of IPCC AR6 (Fox-Kemper et al., 2021a) for a summary of the key drivers of SLC.

Key advances in sea-level projections up to IPCC AR6

There have been substantial methodological and scientific advances in sea-level projections since the publication of the IPCC First Assessment Report in 1990 (Warrick and Oerlemans, 1990). The use of global climate models (GCMs) in IPCC sea-level projections dates back to the IPCC Third Assessment Report (Church et al., 2001). In IPCC AR4, climate models from the third phase of the Climate Model Intercomparison Project (CMIP3) were used as the 'backbone' of the process-based GMSL projections (Meehl et al., 2007), with a similar approach adopted for AR5 using the CMIP5 generation of climate models (Church et al., 2013a). A major change for the AR5 was the inclusion of regional projections (following Slangen et al., 2012). The IPCC Special Report on Global Warming of 1.5° for the first time assessed GMSL based on warming levels (Hoegh-Guldberg et al., 2018). The SROCC added new information on the dynamical ice sheet contribution to the AR5 projections (Oppenheimer et al., 2019). The main advance in AR6 was the use of physics-based emulators to ensure consistency of the sea-level projections with the AR6-assessed ECS and global surface air temperature (GSAT).

We will now discuss some of the key differences of the global mean and regional sea-level projections in IPCC AR6 relative to AR5 and SROCC, by explaining what has been done differently, why these changes were made, and what the effects are on the projections. We do not include the SR1.5 projections in this discussion (Hoegh-Guldberg et al., 2018), as the SR1.5 report made a literature-based assessment of GMSL changes for 1.5° and 2°, but did not produce new projections.

Before we discuss the projections, we note that the interpretation and communication of the uncertainties in sea-level projections has varied across the different IPCC assessment reports (Kopp et al., 2022). IPCC reports use calibrated uncertainty language, in which the confidence level is a qualitative reflection of the evidence and agreement, whereas the likelihood metric is a quantitative measure of uncertainty, expressed probabilistically (Box 1.1, Chen et al., 2021). For the *medium confidence* projections in AR5, the 5–95th percentile range of the model ensemble was interpreted as the *likely* range (the central range with about two-thirds probability, 17–83%), with the uncertainty range of all contributions inflated relative to the model spread to account for structural uncertainties arising from the CMIP5 model ensemble. For the sea-level projections in AR6 (Fox-Kemper et al., 2021a, Section 9.6), the *likely* range was redefined as the central range with *at least* two-thirds probability, encompassing the outer 17th to 83rd percentiles of the probability distributions considered in a p-box (e.g., Le Cozannet et al., 2017a). That is, the definition of *likely* range in AR5, SROCC and AR6 is comparable but not exactly the same, and the way of determining the range from the available information is different. The AR6 *medium confidence* projections include estimated distributions for each emissions scenario with two different methodological choices for the Antarctic ice sheet (see Table 1). AR6 also presented a set of *lowconfidence* projections, which include additional contributions from ice sheet processes and estimates for which there is less agreement and/or less evidence (see Table 1).

The methodologies of the projections in AR5, SROCC and AR6 are briefly summarised in Table 1; for more details, we refer to Chapter 13 of AR5 (Church et al., 2013a), Chapter 4 of SROCC (Oppenheimer et al., 2019) and Chapter 9 of AR6 (Fox-Kemper et al., 2021a). We focus on three major elements of the projections that have changed: (1) the use of CMIP5 versus CMIP6 model output and consistency with the assessed ECS (section 'Updated climate model information and the use of emulators'); (2) differences in the approaches to project the contributions to SLC (section 'Differences in the projected contributions to SLC'); (3) the way the reports addressed potential outcomes outside the *likely* range (section 'Sea-level projections outside the likely range').

Updated climate model information and the use of emulators

The majority of the sea-level projections for the 21st century since AR5 have been based on CMIP5 climate model output (Taylor et al., 2012), forced by Representative Concentration Pathways (RCP, Meinshausen et al., 2011), which are scenarios of future greenhouse gas concentrations and aerosol emissions. The projections in AR6 used information from CMIP6 climate models (Eyring et al., 2016), which were forced by Shared Socioeconomic Pathways (SSP, O'Neill et al., 2014): scenarios of socio-economic development (including for instance population change, urbanisation and technological development) in combination with radiative forcing changes (GHG emissions and concentrations). These scenarios are noted as SSP$x-y$, where x denotes the SSP pathway (SSP1 sustainability, SSP2 middle-of-the-road, SSP3 regional rivalry, SSP4 inequality, SSP5 fossil fuel-intensive) and y the radiative concentration level in 2100 in W/m^2. AR6 used five illustrative SSP scenarios: SSP1–1.9 (very low emissions), SSP1–2.6 (low emissions), SSP2–4.5 (intermediate emissions), SSP3–7.0 (high emissions) and SSP5–8.5 (very high emissions).

The ECS from the CMIP6 model ensemble has a higher average and a wider range compared to the CMIP5 model ensemble and compared to the AR6 assessment of ECS (Forster et al., 2021). The consequences of this change in ECS distribution for projections of GMSL change were investigated by Hermans et al. (2021), who used CMIP6 data in combination with the AR5 methodology. They found that, while the projected change in GSAT median and range increased substantially from CMIP5 to CMIP6 (from 1.9 (1.1–2.6) K to 2.5 (1.6–3.5) K under SSP2-RCP4.5, see their Table S2 for additional scenarios), the upper end of the GMSL *likely* range projections at 2100 increased by only 3–7 cm across all scenarios (see their Figures 1 and 3), due to the delayed response of SLC to temperature changes. However, they also found an increase in the end-of-century GMSL rates of up to ~20%, suggesting that differences between CMIP5 and CMIP6-based GMSL projections could become substantially larger on longer time scales.

One of the novel aspects of AR6 was the use of a physically-based emulator, which allowed for projections of 21st century GSAT and SLC that were consistent with the AR6 assessment of ECS (Forster et al., 2021). The AR6 used a simple two-layer energy balance model (e.g., Geoffroy et al., 2013). Previous studies have used this two-layer model to successfully emulate CMIP5 model projections of GSAT and global mean thermosteric SLC to 2300 (Palmer et al., 2018; Yuan and Kopp, 2021). The AR6 emulator ensemble was constrained using four observational targets, including historical GSAT change and ocean heat uptake (Smith et al., 2021). The projected ocean heat uptake was translated to global mean thermosteric SLC using CMIP6-based estimates of expansion efficiency (Fox-Kemper et al., 2021b). The GSAT changes were also used as input for the land-ice contributions to GMSL rise, which were generated with additional emulators applied to suites of coordinated community efforts for the ice sheet (LARMIP-2, Levermann et al., 2020; ISMIP6, Nowicki et al., 2016) and glacier model (GlacierMIP2, Marzeion et al., 2020) simulations carried out for AR6.

Differences in the projected contributions to SLC

In AR5, the assessments of glacier and ice sheet contributions were based on a range of individual models and publications. The only difference in the SROCC projections with respect to AR5 was the reassessment of the Antarctic dynamics contribution, by replacing the AR5 Antarctic scenario-independent ice dynamic projections with scenario-dependent process-based model estimates (Levermann et al., 2014; Golledge et al., 2015; Ritz et al., 2015; Bulthuis et al., 2019; Golledge et al., 2019). This led to a decrease in 21st century GMSL change compared with AR5 for the RCP2.6 scenario, and an increase for the RCP8.5 scenario (medians and *likely* ranges; Figure 1a,b). However, the scenario-dependence in SROCC may have been amplified because two model estimates did not include accumulation changes (Levermann et al., 2014; Ritz et al., 2015), which are projected to increase with warming and partially counteract dynamic losses (Fox-Kemper et al., 2021a).

For the AR6 projections, statistical emulators were applied to the ISMIP6 and GlacierMIP2 outputs, using the Gaussian process model described in Edwards et al. (2021). For LARMIP-2, results for Antarctic ice sheet dynamics were emulated using an impulse-response function model following (Levermann et al., 2020), augmented by a parametric surface-mass balance model following AR5. There were several motivations for using these emulators: (1) to constrain the projections to the assessed ECS range, an approach that represents a marked change from previous IPCC

Table 1. High-level summary of the methods used in the AR5, SROCC and AR6 reports to project global mean and regional SLC (1° × 1° resolution) to 2100

	AR5	SROCC	AR6
Climate models	CMIP5 (Taylor et al., 2012)		CMIP6 (Eyring et al., 2016)
Scenarios	Representative Concentration Pathways; RCP (Meinshausen et al., 2011)		Shared Socio-Economic Pathways scenarios (O'Neill et al., 2014), see section 'Updated climate model information and the use of emulators'
Reference period for projections	1986–2005		1995–2014
Methods used for projections			
Ocean dynamics and thermal expansion	Mean and standard deviation of a 21-member ensemble of CMIP5 climate models (*zostoga* + *zos*). For GMSL, *zostoga* timeseries were generated by Monte Carlo		Multivariate *t*-distribution fitted to the ocean dynamic sea level from CMIP6, and drawing from this distribution, the ocean dynamic sea level is combined with the emulator-based global mean thermosteric projections. This approach accounts for the underlying correlation between global mean thermosteric sea level rise and ocean dynamic sea level change in CMIP6 (IPCC AR6 WG1 9.SM.4.2–3)
Glaciers (including peripheral glaciers)	Global Mean Surface Temperature (GMST) timeseries generated by Monte Carlo using mean and standard deviation from the same CMIP5 ensemble as and correlated with *zostoga.* Glacier contributions obtained by Monte Carlo as a function of GMST using a parameterisation with systematic uncertainty, derived by fitting the output of CMIP5-forced glacier models		Gaussian process emulator (Edwards et al., 2021) of GlacierMIP2 glacier model output. All glacier models were forced by output from 10 CMIP5 climate models, and two glacier models also used output from 13 CMIP6 models (Marzeion et al., 2020). Initial conditions based on Randolph Glacier Inventory Version 6 (RGI Consortium 2017) and initial ice thickness and volume from an update of (Huss and Farinotti, 2012). (details in Fox-Kemper et al., 2021a, Box 9.3)
Antarctic Ice Sheet	SMB: Calculated from GMST Monte Carlo timeseries, using accumulation and its systematic uncertainty as a function of GMST, by fitting the output of a high-resolution CMIP3-forced SMB model Dynamics: Scenario-independent with uncertainty based on multi-model assessment. The potential for sea level change outside the *likely* range was recognised but could not yet be quantified	SMB: Calculated from GMST Monte Carlo timeseries, using accumulation and its systematic uncertainty as a function of GMST, by fitting the output of a high-resolution CMIP3-forced SMB model. Dynamics: Scenario-dependent model estimate based on Levermann et al. (2014), Golledge et al. (2015), Ritz et al. (2015), Bulthuis et al. (2019), Golledge et al. (2019)	*Medium confidence* processes (*likely* range projections): Processes included are surface mass balance and ice dynamics, including marine ice sheet instability Estimated using a p-box of 2 methods: (1) Gaussian process emulator (Edwards et al., 2021) of ISMIP6 (Nowicki et al., 2016) and (2) LARMIP-2 (Levermann et al., 2020) augmented by AR5 SMB. Where rates were needed, a p-box of (1) AR5 AIS methodology and (2) LARMIP-2 augmented with AR5 SMB was used ISMIP6 ice sheet models used SMB and surface air temperature anomalies from CMIP5 and CMIP6 models (details in Fox-Kemper et al., 2021a, Box 9.3) *Low confidence* processes: Processes also include MICI and other potential processes leading to rapid ice sheet change currently not included in the models (based on SEJ) Estimated using: (1) Structured Expert Judgement (Bamber et al., 2019) and (2) model simulations with MICI (DeConto et al., 2021)
Greenland Ice Sheet	SMB: Calculated from GMST Monte Carlo timeseries, using a formula for SMB and its systematic uncertainty as a function of GMST, by fitting the output of a high-resolution CMIP5-forced SMB model Dynamics: scenario-independent with uncertainty based on multi-model assessment		*Medium confidence* processes: Gaussian process emulator (Edwards et al., 2021) of ISMIP6 (Nowicki et al., 2016). Where rates were needed, an AR5 parametric model fitted to ISMIP6 was used ISMIP6 ice sheet models used SMB and surface are temperature anomalies from CMIP5 and CMIP6 models, downscaled

(*Continued*)

Table 1. (*Continued*)

	AR5	SROCC	AR6
			using regional model MAR (Hofer et al., 2020) (details in Fox-Kemper et al., 2021a, Box 9.3) *Low confidence* processes: Structured Expert Judgement (Bamber et al., 2019)
Land-water storage (LWS) change	Scenario-independent with uncertainty encompassing various alternatives, including persistence of historical rates of groundwater depletion (Konikow, 2011) and dam impoundment (Chao et al., 2008), projections of socioeconomic and surface hydrology models (Wada et al., 2012), and no future change in impoundment		Derived statistical relationships for population and groundwater depletion (Konikow, 2011; Wada et al., 2012, 2016), and population and dam impoundment (Chao et al., 2008; Hawley et al., 2020), scenario-dependent on SSP population changes (Kopp et al., 2014)
Vertical land motion (VLM)	Relative sea-level contribution derived from global GIA models, assuming constant rates		Constant rates of VLM and the geoid component of GIA estimated from the Gaussian process spatiotemporal statistical model of tide-gauge data and GIA model (Kopp et al., 2014) with updated tide gauge observations
Gravitational, rotational, and deformational (GRD) effects	Self-consistent sea-level equation solver (Slangen et al., 2012, 2014a) to compute annual sea-level fingerprints for each of the mass change contributions; driven by regional distributions of glacier changes (fingerprints for 19 regions, based on Randolph Glacier Inventory), ice sheet changes (fingerprints for Greenland, East Antarctica, West Antarctica) and LWS changes (fingerprint based on 2100 regional distribution from Wada et al. (2012))		

Note. This is an adapted version of Table 9.7 in Fox-Kemper et al. (2021a).

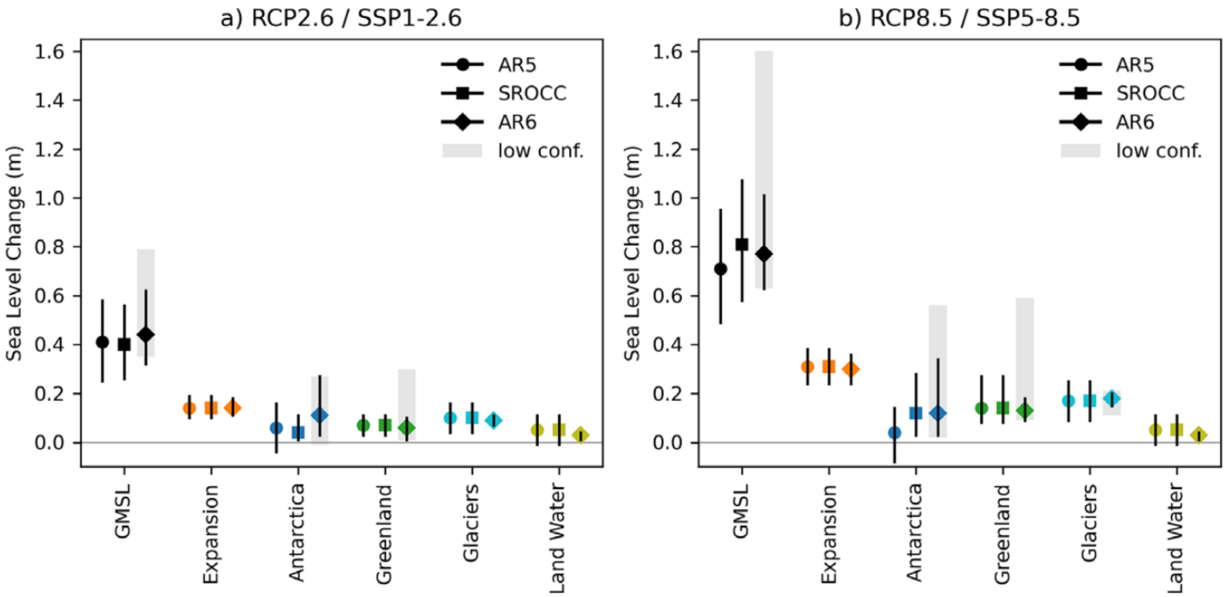

Figure 1. Comparison of 21st century projections of global mean SLC in AR5, SROCC and AR6. Total GMSL and individual contributions, between 1995 and 2014 and 2100 (m), median values and likely ranges of medium confidence projections, for (a) RCP2.6/SSP1–2.6 and (b) RCP8.5/SSP5–8.5. See also Table 9.8 in Fox-Kemper et al. (2021a) for comparative numbers of GMSL projections. AR6 low confidence projections for SSP1–2.6 and SSP5–8.5 in grey for Greenland, Antarctica and GMSL. Corrections for the differences in baseline period between AR5 (1986–2005) and AR6 (1995–2014) were done following IPCC AR6, Table 9.8.

reports; (2) to be able to make projections across all five illustrative SSP scenarios of AR6, as the ice sheet and glacier contributions were mostly based on CMIP5 RCP scenarios; and (3) to sample modelling uncertainties more thoroughly, estimating probability distributions for the contributions. The use of simple climate models and emulators is a trade-off between a more complete exploration of the uncertainties which can be done due to the computational speed of the emulators (compared to the full ice sheet and glacier models, which are limited by constraints of computing and person time), and the potential biases introduced by the necessary assumptions of a simpler model (Edwards et al., 2021). The Gaussian process emulator performed well for the cumulative change in time, but did not account for temporal correlation, so the rates could not be estimated from the emulator. As a consequence, in contexts where rates were needed, AR6 used simpler parametric emulators, based on approaches used in AR5.

A comparison of the GMSL projections to 2100 in the different reports reveals a number of differences (Figure 1a,b). In the land ice

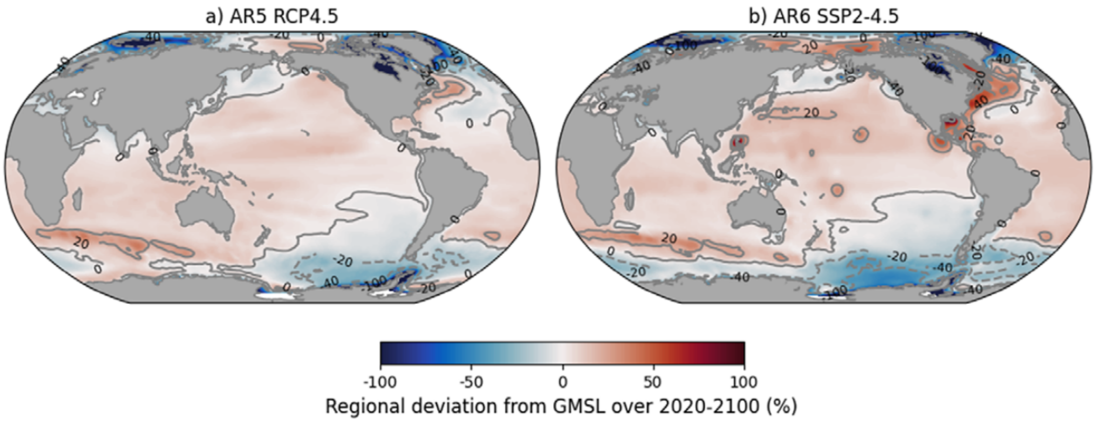

Figure 2. Comparison of regional relative sea-level change w.r.t. the global mean sea-level change in AR5 and AR6 (2020–2100) (%), based on median values, for (a) IPCC AR5 RCP4.5, global mean of 0.46 m and (b) IPCC AR6 SSP2–4.5, global mean of 0.51 m.

contributions, we see a narrowing of the likely ranges for glaciers (under both scenarios) and the Greenland ice sheet (under SSP5–8.5), and a widening of the Antarctic ice sheet *likely* range. The latter is wider as it is based on a p-box bounding distribution functions from the ISMIP6 emulator and LARMIP-2 (Table 1), where the presented *likely* range spans from the lowest 17th to the highest 83rd percentile of the considered methods. The ECS-constrained temperature projections in AR6 (section 'Updated climate model information and the use of emulators') used as input to the land ice emulators show a marked reduction in the width of the *likely* range at 2100 (~0.7 K for SSP1–2.6; ~1.9 K for SSP5–8.5) compared with the 21 CMIP5 models used as the basis of the AR5 sea-level projections (~1.6 K for RCP2.6; ~2.8 K for RCP8.5), which could also be one of the reasons for the reduced width of the glacier and Greenland *likely* ranges. The glacier range may also be slightly underestimated because each region is emulated independently, which means the projections do not account for covariances in the regional uncertainties apart from those associates with a common dependence on temperature (Marzeion et al., 2020; Fox-Kemper et al., 2021a, Section 9.5). However, the AR5 glacier and Greenland uncertainties were open-ended (≥ 66% ranges) and essentially estimated with expert judgement, at a time of far less information from – and confidence in – these process-based models, so the narrowing range is also consistent with an improving evidence base. The land-water storage contribution is reduced in AR6 compared with AR5 due to the use of a different methodology which now links land-water storage changes to global population under SSP scenarios (Kopp et al., 2014), in combination with a larger negative reservoir impoundment contribution from Hawley et al. (2020).

AR5 used different methodologies for estimating the uncertainties in GMSL (Figure 1a,b) and regional SLC (Church et al., 2013b). In contrast, the AR6 GMSL (Figure 1a,b) and regional projected uncertainties are combined in the same way, with the different contributions all treated as conditionally independent given GSAT, which is an input for the emulator (Fox-Kemper et al., 2021b). The total projected GMSL for SSP1–2.6 has increased in AR6 compared with RCP2.6 projections in AR5 and SROCC, with a similar *likely* range (Figure 1a), but with different relative contributions of each component. For SSP5–8.5, the AR6 GMSL projections are 4 cm lower than RCP8.5 in SROCC but 6 cm higher than RCP8.5 in AR5 (Figure 1b), due to differences in the model estimates included (from AR5 to SROCC) and in both models used and the methods used to combine the models (from SROCC to AR6) of the projected Antarctic contribution.

The regional projections (Figure 2) show that SLC is spatially highly variable, due to a combination of ocean dynamic changes, gravitational, rotational and deformation (GRD) effects in response to present-day mass changes, and long-term Glacial Isostatic Adjustment (GIA). There is an overall agreement in the patterns between AR5 and AR6. Some differences arise from the vertical land motion (VLM) contribution, which included only GIA in AR5 and also other VLM contributions, such as tectonics, compaction or anthropogenic subsidence, in AR6: compare for instance the larger ratios along the US East Coast (Figure 2b) to the VLM contribution in Figure 9.26 from Fox-Kemper et al. (2021a). The increased contribution from Antarctica compared to AR5, in combination with the ocean dynamics contribution, leads to a more widespread below-average SLC in the Antarctic Circumpolar Current region.

Sea-level projections outside the likely range

One of the key uncertainties in sea-level projections is the dynamic contribution of the ice sheets (i.e., processes related to the flow of the ice). AR5 assessed the *likely* dynamical contribution of the Antarctic Ice Sheet by 2100 at −2 to 18.5 cm, but also noted that *'Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century. There is medium confidence that this additional contribution would not exceed several tenths of a metre of sea level rise during the 21st century'*. An ice sheet estimate based on SEJ was available at the time of AR5 but this could not be supported by other lines of evidence (Church et al., 2013a). Including the SEJ estimates would have led to an assessment that could not be transparently linked to physical evidence, as the reasoning of the experts involved in the SEJ exercise is undocumented, and it was decided not to use it for the AR5 assessment.

After AR5, following for instance Sutton (2019), *low probability* estimates were increasingly used in the context of risk assessment and to discuss less likely outcomes for risk-averse users (e.g., Le Cozannet et al., 2017b; Hinkel et al., 2019; Nicholls et al., 2021). SROCC argued that stakeholders with a low risk tolerance might use the SEJ numbers (e.g., their Figure 4.2). Model results including marine ice cliff instability (MICI, Deconto and Pollard, 2016) were not used in the main projections of SROCC because the too high surface melt rates led to an uncertain timing and magnitude in the simulated ice loss. In AR6, a set of *low confidence* projections was presented (shown in grey in Figure 1a,b) which build on the *medium confidence* projections. These projections include additional contributions for the ice sheets, estimated using a p-box approach (e.g., Le Cozannet et al., 2017a), considering SEJ (Bamber et al., 2019) together with an improved model-based estimate for Antarctica which included MICI (DeConto et al., 2021). It is important to note that the *low confidence* ranges represent the breadth of literature estimates available at the time, but that they are not incorporated in the assessed *likely* ranges.

The AR6 *low confidence* projections suggest that by 2100, under SSP1–2.6 (Figure 1a), there is a potential Greenland contribution outside the likely range, based on SEJ. For Antarctica, the *medium confidence* SSP1–2.6 projections already include a wide range of values, so the impact of SEJ and MICI estimates in the *lowconfidence* projections is less distinct. Under SSP5–8.5 (Figure 1b), the upper values of the AR6 *low confidence* projections for both ice sheets are considerably larger than the corresponding *medium confidence* estimates. This reflects the deep uncertainty in the literature on the Antarctic contribution (see also Box 9.4 in Fox-Kemper et al., 2021a). What is needed to reduce this deep uncertainty is primarily a better understanding of the physical processes. This will lead to more physically-based model projections with larger ensembles, which will allow for a better exploration of the uncertainties.

Comparison of the AR5 model simulations with observations

In the previous section, we discussed 'how we got here': the developments that led to the most recent IPCC projections. However, it is also relevant to see 'where we are', by comparing the observed sea-level change against sea-level projections for their overlapping period. We evaluate the assessed *likely* ranges of the AR5 projections (from 2007 onwards, Church et al., 2013a) against the assessed observational time series from AR6 (up to 2018, Fox-Kemper et al., 2021a, Table 9.5), both for the total GMSL and the individual contributions (Figure 3).

For GMSL, Antarctica, Greenland and thermal expansion, the observational timeseries are close to the centre of the projections and the estimated rates of change are highly consistent

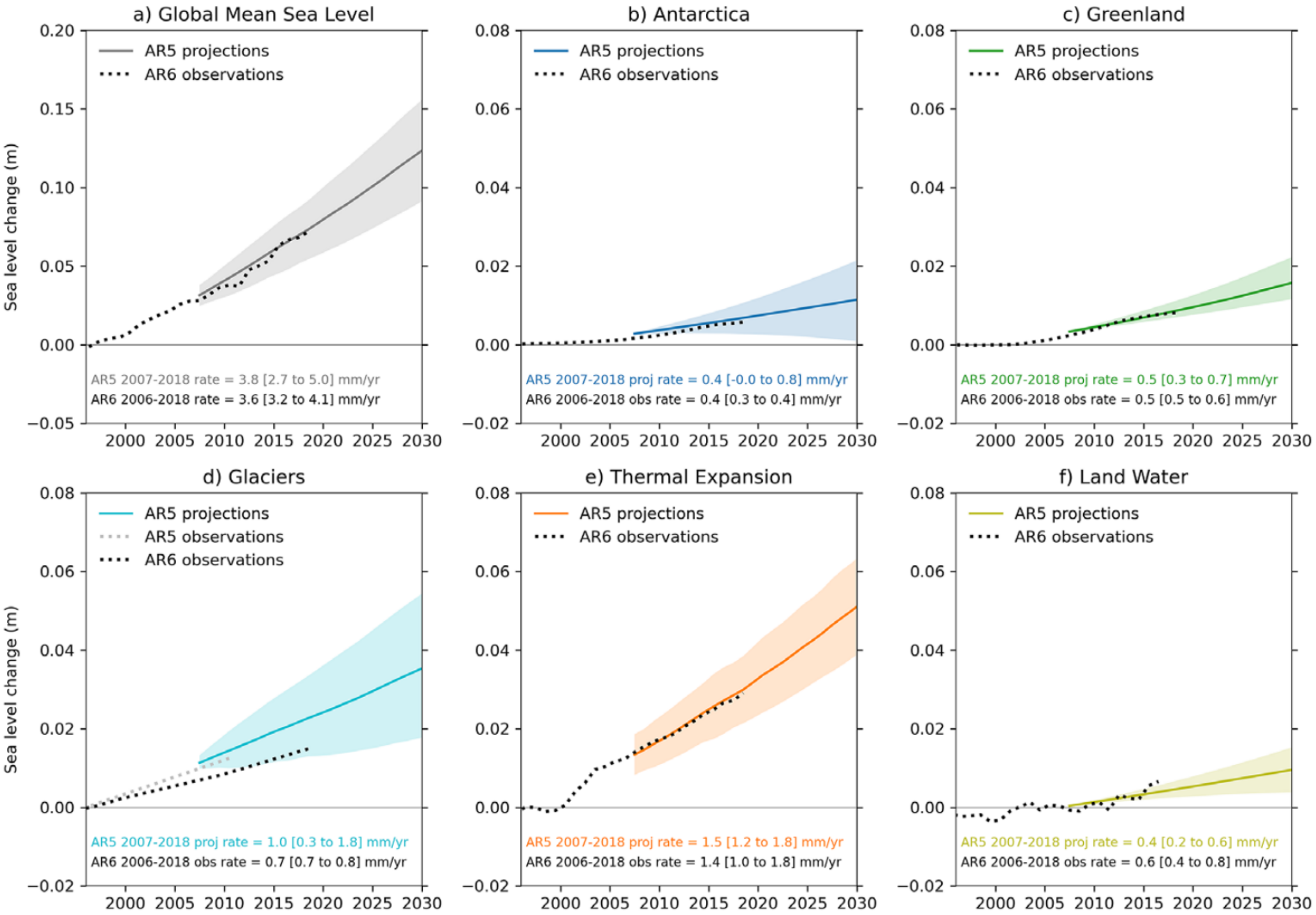

Figure 3. Comparison of observations (IPCC AR6, available up to 2018) and projections (IPCC AR5, available from 2007) of GMSL change. (a) Total GMSL and (b-f) individual contributions in (m) with respect to the period 1986–2005; all uncertainties recomputed to represent the likely range. Text in panels compares rates (mm/yr) of observations for 2006–2018 (Fox-Kemper et al., 2021a, Table 9.5) to rates of projections for 2007–2018 (Church et al., 2013a); rates rounded to nearest 0.1 mm/yr; time periods used for rates differ by 1 year, allowing for traceability to the IPCC reports. Note that AR5 included the Greenland peripheral glaciers in the glacier contribution, whereas AR6 included it in the Greenland contribution; we have therefore subtracted a Greenland peripheral glacier estimate of 0.1 mm/yr from the AR6 Greenland observations in (c) and added it to the AR6 glacier observations in (d), both for the time series and the rates (Church et al., 2013a, Table 13.1; Fox-Kemper et al., 2021b, Table 9.SM.2). The AR5 observed glacier change is added to (d) for reference (using the 1993–2010 linear rate from Table 13.1 of Church et al., 2013a).

(Figure 3a,b,c,e). The observed glacier timeseries in AR6 is at the lower end of the projections, even though the observed rates entirely fall within the likely range of the projected rates (Figure 3d). It is worth noting that the AR5 included glaciers peripheral to the Greenland Ice Sheet in the glacier projections (their Table 13.5), which according to the observations in their Table 13.1 adds a contribution in the order of 0.1 mm/yr. In AR6, this was included in the Greenland contribution. To facilitate the comparison, we have included the observed Greenland peripheral glacier estimate in Figure 3d (Glaciers) and subtracted it from the observations in Figure 3c (Greenland), based on linear rates presented in Church et al., 2013a and Fox-Kemper et al., 2021a. In addition, the glacier contributions since AR5 suggest a smaller glacier contribution, both in observations and projections (for the observations: grey dashed line in Figure 3d based on Church et al., 2013a, Table 13.1 shows a higher rate than AR6, for the projections: Marzeion et al., 2015). The observed rate of land-water change is larger than the projected central value, but the observed time series, despite its interannual variability, mostly falls within the projected *likely* range. The observed rate of change is at the upper bound of the *likely* range projections (Figure 3f).

Wang et al. (2021a) also evaluated GMSL and regional projections from AR5 and SROCC against different tide gauge and altimetry time series for the period 2007–2018. They found that the GMSL trends for 2007–2018 from AR5 projections are almost identical to observed trends and well within the 90% confidence interval. They also showed significant local differences between observations and models, which could be improved with better VLM estimates and minimisation of the internal variability.

A study by Lyu et al. (2021) focused on ocean warming, with the purpose of constraining projections. They compared the observations of ocean temperature by the Argo array (2005–2019) with model simulations from the CMIP5 and CMIP6 databases. They found that (1) the range of CMIP6 has shifted upwards compared with CMIP5; (2) there is a high correlation between observations and models over the Argo period; (3) the emergent constraint indicates that the larger trend of thermosteric SLC in the CMIP6 archive needs to be taken with caution. This supports the AR6 approach, where an emulator was used to constrain the thermosteric SLC of CMIP6 models with the assessed ECS range (section 'Updated climate model information and the use of emulators'), leading to thermosteric SLC projections similar to AR5 and the constrained Lyu et al. (2021) projections.

Moving towards local information

AR5 was the first IPCC assessment report to show regional sea-level projections in addition to GMSL projections, by including the effects of changes in ocean density and circulation, GIA and GRD effects (Table 1). SROCC built on AR5 but explored regional changes in sea-level extremes in more depth. In AR6 as a whole, even stronger emphasis was put on regional climate changes and on using regional information for impacts and risk assessment, in particular in Chapter 10 (Doblas-Reyes et al., 2021), Chapter 12 (Ranasinghe et al., 2021) and the Interactive Atlas (Gutiérrez et al., 2021). The IPCC authors and the IPCC Technical Support Unit also collaborated with NASA to develop the NASA/IPCC Sea Level Projection Tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool) to provide easy access to global and regional projections. As the need for more detailed sea-level information is becoming increasingly evident (e.g., Le Cozannet et al., 2017b; Hinkel et al., 2019; Nicholls et al., 2021; Durand et al., 2022), we discuss a couple of potential future research avenues which may help to further improve sea-level projections on a regional to local scale.

High-resolution ocean modelling

Ocean dynamic SLC is a major driver of spatial sea-level variability, which is typically derived from CMIP5 and CMIP6 GCM simulations. However, the extent to which GCMs can provide local information is limited because of their relatively low atmosphere and ocean grid resolutions, which are constrained by computational costs. The typical ocean grid resolution of CMIP5 models is approximately 1° by 1° (~100 km). Although the ocean components of some CMIP6 models operate at a 0.25° resolution, the resolution of most CMIP6 models has not increased much relative to CMIP5, and the CMIP5 and CMIP6 simulations of ocean dynamic SLC show similar features (Lyu et al., 2020). These relatively coarse resolutions may lead to misrepresentations of ocean dynamic SLC, particularly in coastal regions in which small-scale and tidal processes and bathymetric features are important. Increasing the resolution of the GCMs requires significant additional computational resources as well as more explicit modelling of high-resolution processes that are currently parameterized.

As an alternative, GCMs can be dynamically downscaled using high-resolution atmosphere or ocean models. Emerging research demonstrates the value of dynamical downscaling for SLC simulations in coastal regions such as the Northwestern European Shelf (Figure 4; Hermans et al., 2020; Chaigneau et al., 2022; Hermans et al., 2022), the Southern Ocean (Zhang et al., 2017), the Mediterranean Sea (Sannino et al., 2022), the marginal seas in the Northwest Pacific Ocean (Liu et al., 2016; Kim et al., 2021), the marginal seas near China (Jin et al., 2021) and the Brazilian continental shelf (Toste et al., 2018), on both annual and sub-annual timescales.

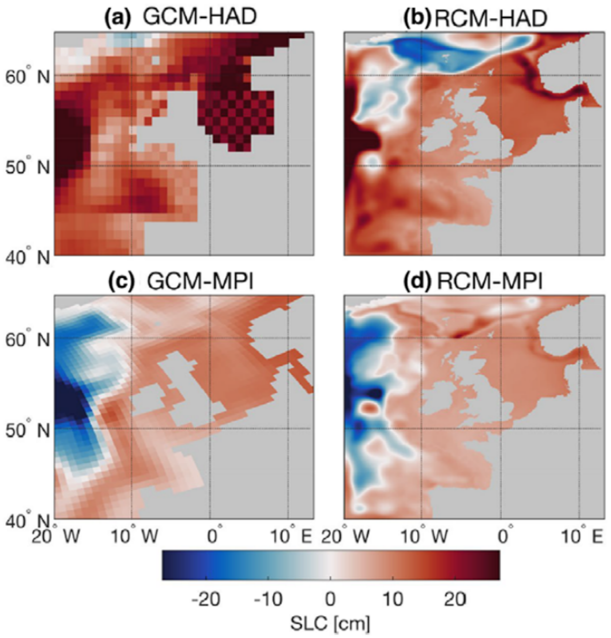

Figure 4. Ocean dynamic SLC northwest of Europe, as simulated by (a) the CMIP5 GCM HadGEM2-ES and (b) dynamically downscaled using regional ocean model NEMO-AMM7, and by (c) the CMIP5 GCM MPI-ESM-LR and (d) dynamically downscaled, for the scenario RCP8.5 (2074–2099 minus 1980–2005). Figure adapted from Hermans et al. (2020).

Additionally, dynamical downscaling can offer a framework in which local changes in tides, surges and waves can be resolved in conjunction with time-mean SLC and incorporated into sea-level projections (Kim et al., 2021; Chaigneau et al., 2022), as it allows for modelling changes at higher temporal frequencies. Dynamical downscaling requires GCM output as boundary conditions, which means that the regional solutions due to the explicit modelling of higher resolution processes should always be considered in the context of the GCM model that is driving the regional model. For instance, for the South China Sea, Jin et al. (2021) found that *'the downscaled results driven by ensemble mean forcings are almost identical to the ensemble average results from individually downscaled cases'*. However, more extensive analysis of the uncertainties associated with dynamical downscaling remains to be done. As a result, the dynamical downscaling of ocean simulations has not yet been systematically applied in the context of regional and local sea-level projections.

Vertical land motion

In addition to the ocean and ice contributions, relative SLC is affected by VLM (Table 1), which may amplify or even dominate the SLC experienced at coastal locations. AR5 and SROCC used GIA models to estimate the VLM contribution to SLC, whereas AR6 based its VLM estimate on the geological background rate at tide gauge stations, derived using the Gaussian Process Model from (Kopp et al., 2014; Table 1). Neither method provides a satisfactory answer, given that the former excludes non-GIA VLM contributions, and the latter requires assumptions regarding the spatio-temporal extrapolation of the tide-gauge derived background rates to areas without tide gauge information by using a GIA model as a prior. AR6, therefore, stated that *'there is low to medium confidence in the GIA and VLM projections employed in this Report. In many regions, higher-fidelity projections would require more detailed regional analysis'*.

Work published after the IPCC AR6 literature deadline has provided new observation-based estimates of VLM for 99 coastal cities based on InSAR observations (Wu et al., 2022) and along the world's coastlines using GNSS data (Oelsmann et al., 2021). However, even with better observational estimates, significant assumptions are required when extrapolating these into the future. Both AR5 and AR6 assume VLM rates remain constant over time, an assumption that is wrong in regions that are tectonically active (where VLM will be nonlinear and stochastic) or where VLM occurs in response to groundwater and gas extractions (which is strongly dependent on societal choices). A potential solution is to use expanded geological reconstructions of paleo sea level on millennial time scales to constrain long-term average trends (Horton et al., 2018b).

Conclusions and future perspectives

In this overview, we have discussed several aspects of sea-level projections: recent developments in the projections, how they compare against observations, and potential future research directions: 'how we got here' (section 'Key advances in sea-level projections up to IPCC AR6'), 'where we are' (section 'Comparison of the AR5 model simulations with observations') and 'where we're going' (section 'Moving towards local information').

Key differences between AR5, SROCC and AR6 include the use of new climate model information (CMIP6) and the use of emulators to constrain the projections to the AR6 assessment of Equilibrium Climate Sensitivity (section 'Updated climate model information and the use of emulators'), new information for the different projected contributions to sea-level change (section 'Differences in the projected contributions to SLC'), and the treatment of projections outside the *likely* range (section 'Sea-level projections outside the likely range').

The *likely* range projections of GMSL and regional SLC at 2100 show relatively modest changes from AR5 to SROCC and AR6, given approximately equivalent climate change scenarios (sections 'Updated climate model information and the use of emulators' and 'Differences in the projected contributions to SLC'): under RCP2.6/SSP1–2.6 from 0.25–0.58 m (AR5) to 0.33–0.62 m (AR6); under RCP8.5/SSP5–8.5 from 0.49–0.95 m (AR5) to 0.63–1.01 m (AR6). Substantial reductions in the uncertainty of the Greenland and glacier contributions to GMSL at 2100 under SSP5–8.5 for AR6 are counterbalanced by an increase in the Antarctic uncertainty, which leads to relatively small changes in overall uncertainty at 2100 between AR5 and AR6.

In AR6, the explicit inclusion of *low confidence* projections highlighted the deep uncertainty associated with the dynamical ice sheet contribution (section 'Sea-level projections outside the likely range'), which was communicated through the use of 'low-likelihood high-impact' storylines (IPCC, 2021; Fox-Kemper et al., 2021a). Regional SLC projections based on the *low confidence* projections were also provided by AR6, but we highlight that more work is needed on understanding and physical modelling of the ice sheet contributions, and on the potential for different regional estimates associated with the partitioning of Greenland and Antarctic ice mass loss.

Our comparison of AR5 projections with observations for the period 2007–2018 shows that the rates of change agree within uncertainties for GMSL and for individual contributions (section 'Comparison of the AR5 model simulations with observations'), which is in line with previous studies focusing on total sea-level change (Wang et al., 2021a) and the ocean heat uptake contribution (Lyu et al., 2021). Monitoring the projections against observed changes is important as it can help to constrain future projections.

In terms of future developments of sea-level projections (section 'Moving towards local information'), we highlight the need for dynamical ocean downscaling to represent processes missing in GCMs, such as tidal effects and local currents in shelf sea regions, to better estimate future ocean dynamic SLC. This would also improve simulations of key small-scale processes at the ocean-ice interface that affect the climatic drivers of ice sheets and therefore projections of their future evolution. It would also lead to a better quantification of the effects on mean SLC on, for example, tidal characteristics and wave propagations to understand the potential compounding effects on future coastal flood hazards. A second aspect that is relevant to relative sea-level projections, in particular in low-lying delta regions, is the need for improved VLM observational estimates and projections. This will particularly impact coastal SLC projections, as flood risks depend on (and in some parts of the world are dominated by) the movement of the land in addition to the changes in water level.

In this paper, we have focused on sea-level projections up to 2100. However, it is important to note that sea-level change does not stop in 2100. Currently, projections beyond 2100 are typically based on different methods compared with the projections up to 2100, due to a lack of model simulations and literature. For instance, in AR6 the time series were extended to 2150 assuming constant ice sheet rates post 2100 and the Gaussian process emulators were substituted with parametric fits. Unfortunately, the use of different methods tends to lead to discontinuities in the time series. To fill this gap, we need better understanding and process modelling of the different components, such that consistent methods can be used to generate long-term projections for the next IPCC assessment report and beyond. This will allow investigations of for instance the sea-level response to surface warming overshoot scenarios, or the inclusion of tipping points in sea-level projections (e.g., Lenton et al., 2019). These are only some of the many potential research avenues associated with long-term sea-level projections, all of which are important to investigate given the long-lasting commitment and widespread consequences of future sea-level rise.

Open peer review. To view the open peer review materials for this article, please visit http://doi.org/10.1017/cft.2022.8.

Data availability statement. All data used for the figures are publicly available from the following sources: IPCC AR5 sea-level projections: https://www.cen.uni-hamburg.de/en/icdc/data/ocean/ar5-slr.html; IPCC SROCC sea-level projections: https://ipcc-temp.s3.eu-central-1.amazonaws.com/SROCC_Ch04-SM_DataFiles.zip; IPCC AR6 sea-level projections: https://doi.org/10.5281/zenodo.5914709, with supplemental data sets documented at https://github.com/Rutgers-ESSP/IPCC-AR6-Sea-Level-Projections and IPCC AR6 sea-level observations: https://github.com/BrodiePearson/IPCC_AR6_Chapter9_Figures (Cross-Chapter Box 9.1 data).

Acknowledgements. We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP and ISMIP6. We thank the climate modelling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access and the multiple funding agencies that support CMIP and ESGF.

Author contributions. M.D.P. conceived the study. A.B.A.S. led the writing of the manuscript. M.D.P., A.B.A.S., C.M.L.C. and T.H.J.H. produced figures. All authors contributed to writing the text and revising the manuscript.

Financial support. A.B.A.S., T.L.E., V.M.S. and T.H.J.H. were supported by PROTECT. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869304, PROTECT contribution number 51. M.D.P., H.H. and J.M.G. were supported by the Met Office Hadley Centre Climate Programme funded by BEIS. C.M.L.C. was supported by the Netherlands Space Office User Support program (grant ALWGO.2017.002). J.A.C. was supported by the Australian Research Council's Discovery Project funding scheme (project DP190101173) and the Australian Research Council Special Research Initiative, Australian Centre for Excellence in Antarctic Science (project SR200100008). T.H.J.H. and R.S.W.W. were supported by the Netherlands Polar Programme. R.E.K. and G.G.G. were supported by the U.S. National Aeronautics and Space Administration (grants 80NSSC17K0698, 80NSSC20K1724 and 80NSSC21K0322 and JPL task 105393.509496.02.08.13.31), and the U.S. National Science Foundation (ICER-1663807 and ICER-2103754, as part of the Megalopolitan Coastal Transformation Hub).

Competing interest. The authors declare none.

References

Bakker AMR, Wong TE, Ruckert KL and Keller K (2017) Sea-level projections representing the deeply uncertain contribution of the West Antarctic ice sheet. *Scientific Reports* **7**(1), 3880.

Bamber JL, Oppenheimer M, Kopp RE, Aspinall WP and Cooke RM (2019) Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences of the United States of America* **116**(23), 11195–11200.

Bittermann K, Rahmstorf S, Kopp RE and Kemp AC (2017) Global mean sea-level rise in a world agreed upon in Paris. *Environmental Research Letters* **12** (12), 124010. http://doi.org/10.1088/1748-9326/aa9def.

Buchanan MK, Oppenheimer M and Kopp RE (2017) Amplification of flood frequencies with local sea level rise and emerging flood regimes. *Environmental Research Letters* **12**(6), 064009. http://doi.org/10.1088/1748-9326/aa6cb3.

Bulthuis K, Arnst M, Sun S and Pattyn F (2019) Uncertainty quantification of the multi-centennial response of the antarctic ice sheet to climate change. *The Cryosphere* **13**, 1349–1380.

Carson M, Köhl A, Stammer D, Slangen ABA, Katsman CA, van de Wal RSW, Church JA and White NJ (2015) Coastal sea level changes, observed and projected during the 20th and 21st century. *Climatic Change* **134**, 269–281.

Cazenave A and the WCRP Global Sea Level Budget Group (2018) Global sea-level budget 1993-present. *Earth System Science Data* **10**, 1551–1590. http://doi.org/10.5194/essd-10-1551-2018.

Chaigneau AA, Reffray G, Voldoire A and Melet A (2022) IBI-CCS: A regional high-resolution model to simulate sea level in Western Europe. *Geoscientific Model Development* **15**(5), 2035–2062.

Chambers DP, Cazenave A, Champollion N, Dieng H, Llovel W, Forsberg R, von Schuckmann K and Wada Y (2016) Evaluation of the global mean sea level budget between 1993 and 2014. *Surveys in Geophysics* **38**(1), 1–19.

Chen D, Rojas M, Samset BH, Cobb K, Diongue Niang A, Edwards PE, mori S, Faria SH, Hawkins E, Hope P, Huybrechts P, Meinshausen M, Mustafa SK, Plattner G-K and Tréguier A-M (2021) Framing, context, and methods. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 147–286.

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D and Unnikrishnan AS (2013a) Sea level change. In Stocker TF, Qin D, Plattner G-K and Midgley PM (eds), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D and Unnikrishnan AS (2013b) Sea level change supplementary material. In Stocker TF, Qin D, Plattner G-K and Midgley PM (eds), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1137–1216.

Chao BF, Wu YH and Li YS (2008) Impact of artificial reservoir water impoundment on global sea level. *Science (New York, N.Y.)*, **320**(5873), 212–4.

Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D and Woodworth PL (2001) Chapter 11: Changes in sea level. In *Climate Change 2001: The Scientific Basis*. Geneva: IPCC, p. 639.

Church JA, Monselesan D, Gregory JM and Marzeion B (2013c) Evaluating the ability of process based models to project sea-level change. *Environmental Research Letters* **8**(1), 14051.

Clark PU, Church JA, Gregory JM and Payne AJ (2015) Recent Progress in understanding and projecting regional and global mean sea level change. *Current Climate Change Reports* **1**(4), 224–246.

Deconto RM and Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. *Nature* **531**(7596), 591–597.

DeConto RM, Pollard D, Alley RB, Velicogna I, Gasson E, Gomez N, Sadai S, Condron A, Gilford DM, Ashe EL, Kopp RE, Li D and Dutton A (2021) The Paris climate agreement and future sea-level rise from Antarctica. *Nature* **593** (7857), 83–89.

Doblas-Reyes FJ, Sörensson AA, Almazroui M, Dosio A, Gutowski WJ, Haarsma R, Hamdi R, Hewitson B, Kwon W-T, Lamptey BL, Maraun D, Stephenson TS, Takayabu I, Terray L, Turner A and Zuo Z (2021) Linking global to regional climate change. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis.*

Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1363–1512.

Durand G, van den Broeke MR, Le Cozannet G, Edwards TL, Holland PR, Jourdain NC, Marzeion B, Mottram R, Nicholls RJ, Pattyn F, Paul F, Slangen ABA, Winkelmann R, Burgard C, van Calcar CJ, Barré JB, Bataille A and Chapuis A (2022) Sea-level rise: From global perspectives to local services. *Frontiers in Marine Science*, **8**, 709595. http://doi.org/10.3389/fmars.2021.709595.

Edwards TL, Nowicki S, Marzeion B, Hock R, Goelzer H, Seroussi H, Jourdain NC, Slater DA, Turner FE, Smith CJ, McKenna CM, Simon E, Abe-Ouchi A, Gregory JM, Larour E, Lipscomb WH, Payne AJ, Shepherd A, Agosta C, Alexander P, Albrecht T, Anderson B, Asay-Davis X, Aschwanden A, Barthel A, Bliss A, Calov R, Chambers C, Champollion N, Choi Y, Cullather R, Cuzzone J, Dumas C, Felikson D, Fettweis X, Fujita K, Galton-Fenzi BK, Gladstone R, Golledge NR, Greve R, Hattermann T, Hoffman MJ, Humbert A, Huss M, Huybrechts P, Immerzeel W, Kleiner T, Kraaijenbrink P, Le clec'h S, Lee V, Leguy GR, Little CM, Lowry DP, Malles JH, Martin DF, Maussion F, Morlighem M, O'Neill JF, Nias I, Pattyn F, Pelle T, Price SF, Quiquet A, Radić V, Reese R, Rounce DR, Rückamp M, Sakai A, Shafer C, Schlegel NJ, Shannon S, Smith RS, Straneo F, Sun S, Tarasov L, Trusel LD, Van Breedam J, van de Wal RSW, van den Broeke M, Winkelmann R, Zekollari H, Zhao C, Zhang T and Zwinger T (2021) Projected land ice contributions to twenty-first-century sea level rise. *Nature* **593**(7857), 74–82.

Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ and Taylor KE (2016) Overview of the coupled model Intercomparison project phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* **9**(5), 1937–1958.

Forster P, Storelvmo T, Armour K, Collins W, Dufresne J-L, Frame D, Lunt DJ, Mauritsen T, Palmer MD, Watanabe M, Wild M and Zhang H (2021) The Earth's energy budget, climate feedbacks, and climate sensitivity. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054.

Fox-Kemper B, Hewitt HT, Xiao C, Aðalgeirsdóttir G, Drijfhout SS, Edwards TL, Golledge NR, Hemer M, Kopp RE, Krinner G, Mix A, Notz D, Nowicki S, Nurhati IS, Ruiz L, Sallée J-B, Slangen ABA and Yu Y (2021a) Ocean, cryosphere, and sea-level change. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362.

Fox-Kemper B, Hewitt HT, Xiao C, Aðalgeirsdóttir G, Drijfhout SS, Edwards TL, Golledge NR, Hemer M, Kopp RE, Krinner G, Mix A, Notz D, Nowicki S, Nurhati IS, Ruiz L, Sallée J-B, Slangen ABA and Yu Y (2021b) Ocean, cryosphere and sea level change supplementary material. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Frederikse T, Jevrejeva S, Riva REM and Dangendorf S (2018) A consistent sea-level reconstruction and its budget on basin and global scales over 1958–2014. *Journal of Climate* **31**(3), 1267–1280.

Frederikse T, Landerer F, Caron L, Adhikari S, Parkes D, Humphrey VW, Dangendorf S, Hogarth P, Zanna L, Cheng L and Wu YH (2020) The causes of sea-level rise since 1900. *Nature* **584**, 393–397. http://doi.org/10.1038/s41586-020-2591-3.

Frederikse T, Riva R, Kleinherenbrink M, Wada Y, van den Broeke M and Marzeion B (2016) Closing the sea level budget on a regional scale: Trends and variability on the Northwestern European continental shelf. *Geophysical Research Letters* **43**(20),10,864–10,872.

Garner AJ, Weiss JL, Parris A, Kopp RE, Horton RM, Overpeck JT and Arbor A (2018) Evolution of 21 st century sea-level rise projections. *Earth's Future* **6**(11), 1603–1615.

Geoffroy O, Saint-Martin D, Bellon G, Voldoire A, Olivié DJL and Tytéca S (2013) Transient climate response in a two-layer energy-balance model. Part II: Representation of the efficacy of deep-ocean heat uptake and validation for CMIP5 AOGCMs. *Journal of Climate* **26**(6), 1859–1876.

Golledge NR, Keller ED, Gomez N, Naughten KA, Bernales J, Trusel LD and Edwards TL (2019) Global environmental consequences of twenty-first-century ice-sheet melt. *Nature* **566**(7742), 65–72. http://doi.org/10.1038/s41586-019-0889-9.

Golledge NR, Kowalewski DE, Naish TR, Levy RH, Fogwill CJ and Gasson EGW (2015) The multi-millennial Antarctic commitment to future sea-level rise. *Nature* **526**(7573), 421–425.

Goodwin P, Haigh ID, Rohling EJ and Slangen A (2017) A new approach to projecting 21st century sea-level changes and extremes. *Earth's Future* **5**(2), 240–253.

Gregory JM, Bouttes N, Griffies SM, Haak H, Hurlin WJ, Jungclaus J, Kelley M, Lee WG, Marshall J, Romanou A, Saenko OA, Stammer D and Winton M (2016) The flux-anomaly-forced model intercomparison project (FAFMIP) contribution to CMIP6: Investigation of sea-level and ocean climate change in response to CO_2 forcing. *Geoscientific Model Development* **9**(11), 3993–4017.

Gregory JM, Griffies SM, Hughes CW, Lowe JA, Church JA, Fukimori I, Gomez N, Kopp RE, Landerer F, Le Cozannet G, Ponte RM, Stammer D, Tamisiea ME and van de Wal RSW (2019) Concepts and terminology for sea level: Mean, variability and change, both local and global. *Surveys in Geophysics* **40**(6), 1251–1289.

Gregory JM, White NJ, Church JA, Bierkens MFP, Box JE, Van Den Broeke MR, Cogley JG. Fettweis X, Hanna E, Huybrechts P, Konikow LF, Leclercq PW, Marzeion B, Oerlemans J, Tamisiea ME, Wada Y, Wake LM and Van De Wal RSW (2013) Twentieth-century global-mean sea level rise: Is the whole greater than the sum of the parts? *Journal of Climate* **26**(13), 4476–4499.

Grinsted A, Jevrejeva S, Riva REM and Dahl-Jensen D (2015) Sea level rise projections for northern Europe under RCP8.5. *Climate Research* **64**(1), 2015. http://doi.org/10.3354/cr01309.

Gutiérrez JM, Jones RG, Narisma GT, Alves LM, Amjad M, Gorodetskaya IV, Grose M, Klutse NAB, Krakovska S, Li J, Martínez-Castro D, Mearns LO, Mernild SH, Ngo-Duc T, van den Hurk B and Yoon J-H (2021) Atlas. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1927–2058.

Hamlington BD, Gardner AS, Ivins E, Lenaerts JTM, Reager JT, Trossman DS, Zaron ED, Adhikari S, Arendt A, Aschwanden A, Beckley BD, Bekaert DPS, Blewitt G, Caron L, Chambers DP, Chandanpurkar HA, Christianson K, Csatho B, Cullather RI, DeConto RM, Fasullo JT, Frederikse T, Freymueller JT, Gilford DM, Girotto M, Hammond WC, Hock R, Holschuh N, Kopp RE, Landerer F, Larour E, Menemenlis D, Merrifield M, Mitrovica JX, Nerem RS, Nias IJ, Nieves V, Nowicki S, Pangaluru K, Piecuch CG, Ray RD, Rounce DR, Schlegel NJ, Seroussi H, Shirzaei M, Sweet WV, Velicogna I, Vinogradova N, Wahl T, Wiese DN and Willis MJ (2020) Understanding of contemporary regional sea-level change and the implications for the future. *Reviews of Geophysics* **58**(3), e2019RG000672.

Hawley WB, Hay CC, Mitrovica JX and Kopp RE (2020) A spatially variable time series of sea level change due to artificial water impoundment. *Earth's Future* **8**(7), e2020EF001497.

Hermans THJ, Gregory JM, Palmer MD, Ringer MA, Katsman CA and Slangen ABA (2021) Projecting global mean sea-level change using CMIP6 models. *Geophysical Research Letters* **48**(5), e2020GL092064.

Hermans THJ, Katsman CA, Camargo CML, Garner GG, Kopp RE and Slangen ABA (2022) The effect of wind stress on seasonal sea-level change on the Northwestern European shelf. *Journal of Climate* **35**, 1745–1759.

Hermans THJ, Tinker J, Palmer MD, Katsman CA, Vermeersen BLA and Slangen ABA (2020) Improving sea-level projections on the Northwestern European shelf using dynamical downscaling. *Climate Dynamics* **54**(3–4), 1987–2011. http://doi.org/10.1007/s00382-019-05104-5.

Hinkel J, Church JA, Gregory JM, Gregory JM, Lambert E, McInnes K, Nicholls RJ, Church JA, van der Pol T and van de Wal RSW (2019) Meeting user needs for sea level rise information: A decision analysis perspective. *Earth's Future* **7**(3), 320–337.

Hock R, Bliss A, Marzeion B, Giesen RH, Hirabayashi Y, Huss M, Radic V and Slangen ABA (2019) GlacierMIP - A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology* **65**(251), 453–467. http://doi.org/10.1017/jog.2019.22.

Hoegh-Guldberg O, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I, Diedhiou A, Djalante R, Ebi KL, Engelbrecht F, Guiot J, Hijioka Y, Mehrotra S, Payne A, Seneviratne SI, Thomas A, Warren R and Zhou G (2018) Impacts of 1.5°C global warming on natural and human systems. In Masson-Delmotte V, Zhai P, Pörtner H-O, … Waterfield T (eds.) *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change* Cambridge University Press, Cambridge, UK and New York, NY, USA. pp. 175–31.

Hofer S, Lang C, Amory C, Kittel C, Delhasse A, Tedstone A and Fettweis X (2020). Greater Greenland Ice Sheet contribution to global sea level rise in CMIP6. *Nature Communications*, **11**(1), 1–11.

Horton BP, Kopp RE, Garner AJ, Hay CC, Khan NS, Roy K and Shaw TA (2018a) Mapping sea-level change in time, space, and probability. *Annual Review of Environment and Resources* **43**(1), 481–521.

Horton BP, Shennan I, Bradley SL, Cahill N, Kirwan M, Kopp RE and Shaw TA (2018b) Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data. *Nature Communications* **9**(1), 2687.

Huss M and Farinotti D (2012). Distributed ice thickness and volume of all glaciers around the globe. *Journal of Geophysical Research: Earth Surface*, **117**(F4)

IPCC (2021) Summary for policymakers. In Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32.

Jackson LP, Grinsted A and Jevrejeva S (2018) 21st century sea-level rise in line with the Paris accord. *Earth's Future* **6**, 213–229.

Jackson LP and Jevrejeva S (2016) A probabilistic approach to 21st century regional sea-level projections using RCP and high-end scenarios. *Global and Planetary Change* **146**, 179–189.

Jevrejeva S, Jackson LP, Grinsted A, Lincke D and Marzeion B (2018) Flood damage costs under the sea level rise with warming of 1.5°C and 2°C. *Environmental Research Letters* **13**, 074014. http://doi.org/10.1088/1748-9326/aacc76.

Jin Y, Zhang X, Church JA and Bao X (2021) Projected sea level changes in the marginal seas near China based on dynamical downscaling. *Journal of Climate* **34**(17), 7037–7055.

Kim Y-Y, Kim B-G, Jeong KY, Lee E, Byun D-S and Cho Y-K (2021) Local sea-level rise caused by climate change in the Northwest Pacific marginal seas using dynamical downscaling. *Frontiers in Marine Science* **8**, 1924.

Konikow LF (2011). Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophys Res Lett*, **38**(L17401). doi: 10.1029/2011GL048604

Kopp RE, DeConto RM, Bader DA, Hay CC, Horton RM, Kulp S, Oppenheimer M, Pollard D and Strauss BH (2017) Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future* **5**(12), 1217–1233.

Kopp RE, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen DJ, Strauss BH and Tebaldi C (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide gauge sites. *Earth's Future* **2** (8), 383–407.

Kopp RE, Kemp AC, Bittermann K, Horton BP, Donnelly JP, Gehrels WR, Hay CC, Mitrovica JX, Morrow ED and Rahmstorf S (2016) Temperature-driven global sea-level variability in the common era. *Proceedings of the National Academy of Sciences* **113**(11), E1434–E1441.

Kopp RE, Oppenheimer M, O'Reilly J, Drijfhout S, Edwards TL, Fox-Kemper B, Garner GG, Golledge NR, Hermans THJ, Hewitt HT, Horton BP, Krinner G, Notz D, Nowicki SM, Palmer MD, Slangen ABA and Xiao C (2022) *Communicating projection uncertainty and ambiguity in sea-level assessment (submitted). https://www.authorea.com/doi/full/10.1002/essoar.10511663.1*

Le Bars D, Drijfhout S and De Vries H (2017) A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss. *Environmental Research Letters* **12**, 044013. http://doi.org/10.1088/1748-9326/aa6512.

Le Cozannet G, Manceau JC and Rohmer J (2017a) Bounding probabilistic sea-level projections within the framework of the possibility theory. *Environmental Research Letters* **12**, 014012. http://doi.org/10.1088/1748-9326/aa5528.

Le Cozannet G, Nicholls RJ, Hinkel J, Sweet WV, McInnes KL, Van de Wal RSW, Slangen ABA, Lowe JA and White KD (2017b) Sea level change and coastal climate services: The way forward. *Journal of Marine Science and Engineering* **5**(4), 49. http://doi.org/10.3390/jmse5040049.

Lempert RJ, Popper SW and Bankes SC (2003) *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*. Santa Monica, CA: Rand Corporation.

Lenton TM, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W and Schellnhuber HJ (2019) Climate tipping points – Too risky to bet against. *Nature* **575**, 592–595.

Levermann A, Winkelmann R, Albrecht T, Goelzer H, Golledge NR, Greve R, Huybrechts P, Jordan J, Leguy G, Martin D, Morlighem M, Pattyn F, Pollard D, Quiquet A, Rodehacke C, Seroussi H, Sutter J, Zhang T, Van Breedam J, Calov R, Deconto R, Dumas C, Garbe J, Gudmundsson HG, Hoffman MJ, Humbert A, Kleiner T, Lipscomb WH, Meinshausen M, Ng E, Nowicki SMJ, Perego M, Price SF, Saito F, Schlegel NJ, Sun S and Van De Wal RSW (2020) Projecting Antarctica's contribution to future sea level rise from basal ice shelf melt using linear response functions of 16 ice sheet models (LARMIP-2). *Earth System Dynamics* **11**(1), 35–76.

Levermann A, Winkelmann R, Nowicki S, Fastook JL, Frieler K, Greve R, Hellmer HH, Martin MA, Meinshausen M, Mengel M, Payne AJ, Pollard D, Sato T, Timmermann R, Wang WL and Bindschadler RA (2014) Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models. *Earth System Dynamics* **5**(2), 271–293.

Liu ZJ, Minobe S, Sasaki YN and Terada M (2016) Dynamical downscaling of future sea level change in the western North Pacific using ROMS. *Journal of Oceanography* **72**(6), 905–922.

Lyu K, Zhang X and Church JA (2020) Regional dynamic sea level simulated in the CMIP5 and CMIP6 models: Mean biases, future projections, and their linkages. *Journal of Climate* **33**(15), 6377–6398.

Lyu K, Zhang X and Church JA (2021) Projected ocean warming constrained by the ocean observational record. *Nature Climate Change* **11**(10), 834–839.

Marzeion B, Hock R, Anderson B, Bliss A, Champollion N, Fujita K, Huss M, Immerzeel WW, Kraaijenbrink P, Malles JH, Maussion F, Radić V, Rounce DR, Sakai A, Shannon S, van de Wal RSW and Zekollari H (2020) Partitioning the uncertainty of ensemble projections of global glacier mass change. *Earth's Future* **8**(7), e2019EF001470.

Marzeion B, Leclercq PW, Cogley JG and Jarosch AH (2015) Brief communication: Global glacier mass loss reconstructions during the 20th century are consistent. *The Cryosphere Discussions*, June, pp. 1–9.

Meehl GA, Stocker TF, Collins WD, … Zhao Z-C (2007) 2007: Global Climate Projections. In *Climate Change 2007: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva: IPCC, pp. 747–846.

Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, Matsumoto K, Montzka SA, Raper SCB, Riahi K, Thomson A, Velders GJM, van Vuuren DPP (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109**(1–2), 213.

Mengel M, Levermann A, Frieler K, Robinson A, Marzeion B and Winkelmann R (2016) Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences* **113**(10), 2597–2602.

Meyssignac B, Slangen ABA, Melet A, Church JA, Fettweis X, Marzeion B, Agosta C, Ligtenberg SRM, Spada G, Richter K, Palmer MD, Roberts C and Champollion N (2017) Evaluating model simulations of twentieth-century sea-level rise. Part II: Regional Sea-level changes. *Journal of Climate* **30**(21), 8565–8593.

Nauels A, Meinshausen M, Mengel M, Lorbacher K and Wigley TML (2017) Synthesizing long-term sea level rise projections – The MAGICC Sea level model v2.0. *Geoscientific Model Development* **10**(6), 2495–2524.

Nicholls RJ, Hanson SE, Lowe JA, Slangen ABA, Wahl T, Hinkel J and Long AJ (2021) Integrating new sea-level scenarios into coastal risk and adaptation assessments: An ongoing process. *Wiley Interdisciplinary Reviews: Climate Change* **12**(3), 1–27.

Nowicki SMJ, Payne T, Larour E, Seroussi H, Goelzer H, Lipscomb W, Gregory J, Abe-Ouchi A and Shepherd A (2016) Ice sheet model intercomparison project (ISMIP6) contribution to CMIP6. *Geoscientific Model Development Discussions*, pp. 1–42.

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R and van Vuuren DP (2014) A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change* **122**(3), 387–400.

Oelsmann J, Passaro M, Dettmering D, Schwatke C, Sánchez L and Seitz F (2021) The zone of influence: Matching sea level variability from coastal altimetry and tide gauges for vertical land motion estimation. *Ocean Science* **17**(1), 35–57.

Oppenheimer M, Glavovic B, Hinkel J, van de Wal R, Magnan AK, Abd-Elgawad A, Cai R, Cifuentes-Jara M, DeConto RM, Ghosh T, Hay J, Isla F, Marzeion B, Meyssignac B and Sebesvari Z (2019) Chapter 4: Sea level rise and implications for low lying islands, coasts and communities. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge University Press, Cambridge, UK and NewYork, NY, USA, pp. 321–445. http://doi.org/10.1126/science.aam6284.

Palmer MD, Gregory JM, Bagge M, Calvert D, Hagedoorn JM, Howard T, Klemann V, Lowe JA, Roberts CD, Slangen ABA and Spada G (2020) Exploring the drivers of global and Regional Sea-level change over the 21st century and beyond. *Earths Future* **8**, e2019EF001413.

Palmer MD, Harris GR and Gregory JM (2018) Extending CMIP5 projections of global mean temperature change and sea level rise due to thermal expansion using a physically-based emulator. *Environmental Research Letters* **13** (8), 84003.

Perrette M, Landerer F, Riva R, Frieler K and Meinshausen M (2013) A scaling approach to project regional sea level rise and its uncertainties. *Earth System Dynamics* **4**(1), 11–29.

Ranasinghe R, Ruane AC, Vautard R, Arnell N, Coppola E, Cruz FA, Dessai S, Islam AS, Rahimi M, Ruiz CD, Sillmann J, Sylla MB, Tebaldi C, Wang W and Zaaboul R (2021) Climate change information for regional impact and for risk assessment. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA pp. 1767–1926.

Rietbroek R, Brunnabend S-E, Kusche J, Schröter J and Dahle C (2016) Revisiting the contemporary sea-level budget on global and regional scales. *Proceedings of the National Academy of Sciences of the United States of America* **113**(6), 1504–1509.

Ritz C, Edwards TL, Durand G, Payne AJ, Peyaud V and Hindmarsh RCA (2015) Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. *Nature* **58**(7580), 115–118.

Sannino G, Carillo A, Iacono R, Napolitano E, Palma M, Pisacane G and Struglia MV (2022) Modelling present and future climate in the Mediterranean Sea: A focus on sea-level change. *Climate Dynamics* **59**(1–2), 357–391.

Schleussner CF, Lissner TK, Fischer EM, Wohland J, Perrette M, Golly A, Rogelj J, Childers K, Schewe J, Frieler K, Mengel M, Hare W and Schaeffer M (2016) Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth System Dynamics* **7**, 327–351. http://doi.org/10.5194/esd-7-327-2016.

Slangen ABA, Adloff F, Jevrejeva S, Leclercq PW, Marzeion B, Wada Y and Winkelmann R (2017a) A review of recent updates of sea-level projections at global and regional scales. *Surveys in Geophysics* **38**(1), 385–406.

Slangen ABA, Carson M, Katsman CA, van de Wal RSW, Köhl A, Vermeersen LLA and Stammer D (2014a) Projecting twenty-first century regional sea-level changes. *Climatic Change* **124**(1–2), 317–332.

Slangen ABA, Katsman CA, van de Wal RSW, Vermeersen LLA and Riva REM (2012) Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios. *Climate Dynamics* **38**(5–6), 1191–1209.

Slangen ABA, Meyssignac B, Agosta C, Champollion N, Church JA, Fettweis X, Ligtenberg SRM, Marzeion B, Melet A, Palmer MD, Richter K, Roberts CD and Spada G (2017b) Evaluating model simulations of twentieth-century sea level rise. Part I: Global mean sea level change. *Journal of Climate* **30**(21), 8539–8564.

Slangen ABA, Van De Wal RSW, Wada Y and Vermeersen LLA (2014b) Comparing tide gauge observations to regional patterns of sea-level change (1961–2003). *Earth System Dynamics* **5**(1), 243–255.

Smith C, Nicholls ZRJ, Armour K, Collins W, Forster P, Meinshausen M, Palmer MD and Watanabe M (2021) The Earth's energy budget, climate feedbacks, and climate sensitivity supplementary material. In Masson-Delmotte V, Zhai P, Pirani A and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sutton RT (2019) Climate science needs to take risk assessment much more seriously. *Bulletin of the American Meteorological Society* **100**(9), 1637–1642.

Taylor KE, Stouffer RJ and Meehl GA (2012) An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* **93**, 485–498.

The IMBIE Team (2018) Mass balance of the Antarctic ice sheet from 1992 to 2017. *Nature* **558**(7709), 219–222.

The IMBIE Team (2019) Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature* **579**, 233–239. http://doi.org/10.1038/s41586-019-1855-2.

Toste R, Assad LPF and Landau L (2018) Downscaling of the global HadGEM2-ES results to model the future and present-day ocean conditions of the southeastern Brazilian continental shelf. *Climate Dynamics* **51**(1–2), 143–159.

Van de Wal RSW, Zhang X, Minobe S, Jevrejeva S, Riva REM, Little C, Richter K and Palmer MD (2019) Uncertainties in long-term twenty-first century process-based coastal sea-level projections. In *Surveys in Geophysics*. Cham: Springer, pp. 1655–1671.

Wada Y, van Beek LPH, Weiland FCS, Chao BF, Wu Y-H and Bierkens MFP (2012). Past and future contribution of global ground water depletion to sea-level rise. *Geophys Res Lett*, **39**(L09402). doi:10.1029/2012GL051230

Wada Y, Lo M-H, Yeh PJ-F, Reager JT, Famiglietti JS, Wu R-J and Tseng Y-H (2016). Fate of water pumped from underground and contributions to sea-level rise. *Nature Climate Change*. doi:10.1038/NCLIMATE3001

Wang J, Church JA, Zhang X and Chen X (2021a) Reconciling global mean and regional sea level change in projections and observations. *Nature Communications* **12**(1), 1–12.

Wang J, Church JA, Zhang X, Gregory JM, Zanna L and Chen X (2021b) Evaluation of the local sea-level budget at tide gauges since 1958. *Geophysical Research Letters* **48**(20), e2021GL094502.

Warrick R and Oerlemans J (1990) Chapter 9: Sea level rise. In *Climate Change: The IPCC Scientific Assessment*. Cambridge: Cambridge University Press, pp. 259–281.

Wong TE, Bakker A, Ruckert K, Applegate P, Slangen A and Keller K (2017) BRICK v0.1, a simple, accessible, and transparent model framework for climate and regional sea-level projections. *Geoscientific Model Development Discussions* **10**, 2741–2760. http://doi.org/10.5194/gmd-2016-303.

Wu P, Wei M and D'Hondt S (2022) Subsidence in coastal cities throughout the world observed by InSAR. *Geophysical Research Letters* **49**(7), e2022GL098477.

Yuan J and Kopp RE (2021) Emulating ocean dynamic sea level by two-layer pattern scaling. *Journal of Advances in Modeling Earth Systems* **13**(3), e2020MS002323.

Zhang X, Church JA, Monselesan D and McInnes KL (2017) Sea level projections for the Australian region in the 21st century. *Geophysical Research Letters* **44**(16), 8481–8491.