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Global mean sea-level rise in a world agreed upon in Paris

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Abstract

Although the 2015 Paris Agreement seeks to hold global average temperature to '*well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels*', projections of global mean sea-level (GMSL) rise commonly focus on scenarios in which there is a high probability that warming exceeds 1.5 °C. Using a semi-empirical model, we project GMSL changes between now and 2150 CE under a suite of temperature scenarios that satisfy the Paris Agreement temperature targets. The projected magnitude and rate of GMSL rise varies among these low emissions scenarios. Stabilizing temperature at 1.5 °C instead of 2 °C above preindustrial reduces GMSL in 2150 CE by 17 cm (90% credible interval: 14–21 cm) and reduces peak rates of rise by 1.9 mm yr^{-1} (90% credible interval: 1.4–2.6 mm yr^{-1}). Delaying the year of peak temperature has little long-term influence on GMSL, but does reduce the maximum rate of rise. Stabilizing at 2 °C in 2080 CE rather than 2030 CE reduces the peak rate by 2.7 mm yr^{-1} (90% credible interval: 2.0–4.0 mm yr^{-1}).

Introduction

Global mean sea level (GMSL) rise is a central consequence of warming Earth's climate. Median projections for GMSL rise during the 20th century range from 1.3−1.9 mm yr^{-1} (Church and White 2011, Dangendorf *et al* 2017, Hay *et al* 2015, Jevrejeva *et al* 2014, Ray and Douglas 2011, Thompson *et al* 2016, Wenzel and Schröter 2014); the 20th century rate of sea-level rise was also extremely likely the fastest century-scale rate in at least 2700 years (Kopp *et al* 2016a). Recent satellite altimetry measurements indicate that the current, decadal-scale rate of GMSL rise has accelerated to about 3 mm yr^{-1} (Ablain *et al* 2017, Cazenave *et al* 2014, Chen *et al* 2017, Dieng *et al* 2017). Ongoing and future GMSL rise will expose the world's coastlines, with their high population density and concentrations of high-value and high-importance infrastructure and economic activity, to more extensive and frequent flooding, saltwater intrusion, and (in some cases) permanent submergence (Garner *et al* 2017, Lichter *et al* 2010, Marzeion and Levermann 2014,

Moftakhari *et al* 2017, Nicholls *et al* 2011, Rahmstorf 2017, Rasmussen *et al* 2017). Landlocked communities will be affected by sea-level induced migration (Hauer 2017). Coastal ecosystems that provide services such as dampening of storm surges may also be directly impacted (Kirwan *et al* 2010). The severity of these impacts depends on both the magnitude and rate of sealevel rise (Kirwan *et al* 2010) (available at stacks.iop.org/ERL/12/124010/mmedia).

Most recent climate change projections (including those of the Intergovernmental Panel on Climate Change) use the Representative Concentration Pathways (RCPs) (Moss *et al* 2010, van Vuuren *et al* 2012) as scenarios of future greenhouse gas emissions and atmospheric concentrations. In all four RCPs, there is a high probability that global mean surface temperature will be more than 1.5 °C warmer than a pre-industrial baseline (here defined as the 1850–1879 CE mean) by the end of this century. For example, under the lowest-emissions RCP (RCP 2.6), simulations with a probabilistic simple climate model (Meinshausen *et al* 2011) indicate that there is a ∼54% probability of at

least transiently exceeding 1.5 °C before 2150 CE and a ∼20% probability of exceeding 2.0 °C. For RCP 4.5, the probability of exceeding 1.5 °C and 2 °C above pre-industrial temperature before 2150 CE is ∼100% and ∼77%, respectively. In the fossil-fuel intensive RCP 8.5, these thresholds are exceeded with 100% probability. By contrast, the 2015 Paris Agreement seeks to hold the increase in global mean surface temperature (GMST) to '*well below 2.0 °C above preindustrial levels and pursue effort to limit warming to 1.5 °C*' (UNFCCC 2015). Although this target is clearly ambitious (Rogelj *et al* 2016), a range of measures for how to meet it are being discussed (e.g. Figueres *et al* 2017, Rockström *et al* 2017).

The magnitude and rate of future GMSL rise will depend upon future emissions. However, simulations based on the RCPs inadequately characterize this response in a future consistent with the goals of the Paris Agreement. Given the long response time of GMSL rise to climate forcing, a 1.5 °C warming could result in a commitment to multi-century GMSL rise, which will have impacts on policy and coastal management well beyond 2100 CE (Clark *et al* 2016). Furthermore, differences in the possible trajectories taken to reach 1.5 °C may result in different amounts and rates of GMSL rise in the next ∼150 years. To better assess GMSL rise under the goals of the Paris Agreement, we use a semi-empirical sea-level model to generate projections up to 2150 CE using multiple different temperature scenarios in which warming is limited to 2 °C or less.

Semi-empirical model development and calibration

Semi-empirical sea-level models use instrumental observations and/or proxy-based reconstructions to estimate a statistical relationship between temperature and GMSL (Gornitz *et al* 1982, Rahmstorf 2007, Jevrejeva *et al* 2009, Bittermann *et al* 2013, Kopp *et al* 2016a). They were developed as a pragmatic complement to process-based models, which do not yet fully represent the physical behavior of the ocean, cryosphere, atmosphere and their interactions (Rahmstorf 2007, Vermeer and Rahmstorf 2009, Grinsted *et al* 2009).
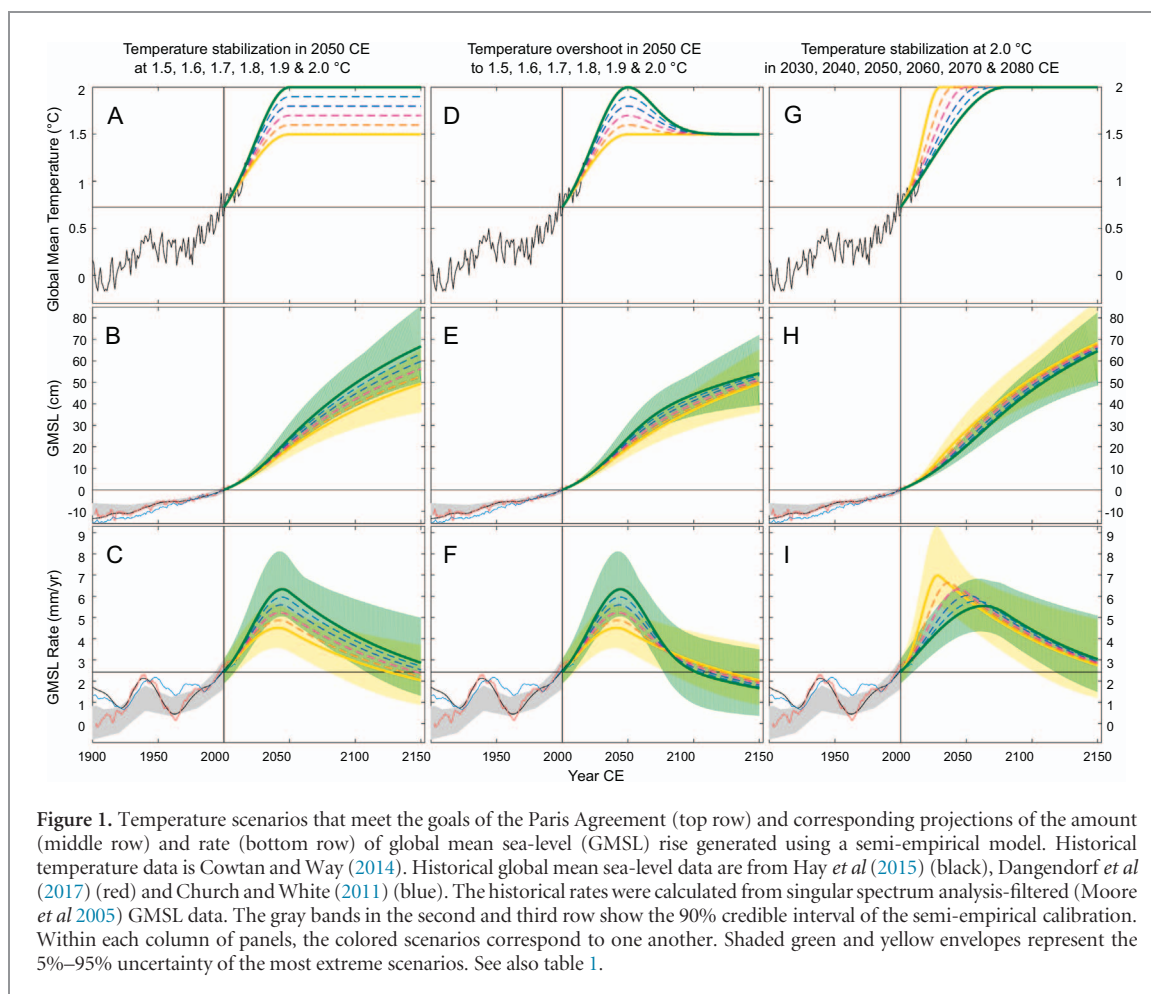
A semi-empirical model projects the GMSL change associated with a specified scenario of future temperature change, assuming the relationship between temperature and rate of GMSL change remains the same as in the calibration data set. One advantage of semi-empirical models is that they are computationally simple, which makes them fast to run and enables GMSL to be projected probabilistically under a large number of temperature scenarios. Another advantage is (by construction) their consistency with the past relationship of temperature and rate of GMSL change.

This second advantage is also a key limitation: semi-empirical models assume that this relationship holds in the future, an assumption which is likely to be invalid

when semi-empirical models are employed to generate projections far into the future or for high-end temperature scenarios. In both of these cases, semi-empirical models are likely to project less GMSL change than process-based models because they do not account for processes not present in the calibration period, such as the non-linearities associated with crossing critical thresholds in ice sheet behavior (Joughin *et al* 2014, Rignot *et al* 2014, Robinson *et al* 2012, Kopp *et al* 2016b, DeConto and Pollard 2016, Kopp *et al* 2017). In West Antarctica for example, the Pine Island and Thwaites Glaciers may have recently crossed a critical threshold for marine ice sheet instability (Joughin *et al* 2014, Rignot *et al* 2014). Similarly, recent work has proposed that marine ice-cliff instability (Bassis and Walker 2011) may become a major mode of retreat in marine-based parts of the Antarctic ice sheet (DeConto and Pollard 2016, Pollard *et al* 2015), although to date it has been observed primarily in a small set of outlet glaciers. These emerging behaviors, poorly represented in the calibration period (as well as in most current ice-sheet models), will not be captured by a semi-empirical model. Therefore, semi-empirical projections should be viewed as lower limits which do not fully represent the high-end tail. However, recent work showing agreement between the process-based GMSL projections preferred by the IPCC's Fifth Assessment Report (Church *et al* 2013) and a semi-empirical model calibrated to the last two millennia (Kopp *et al* 2016a) suggests that semiempirical models are particularly well suited to examining temperature scenarios, such as those consistent with the Paris Agreement, in which the focus is on relatively short-term (next 100–200 years) and small (less than 2.0 °C) temperature changes.

We use the same semi-empirical model as Kopp *et al* (2016a), calibrated using two different reconstructions of global mean temperature over the past ∼2000 years (Mann *et al* 2009, Marcott *et al* 2013). Unless otherwise stated, the presented results combine both calibrations by taking the mean of their medians, the minimum of the lower bounds of 90% credible intervals, and the maximum of upper bounds of 90% credible intervals. GMSL projections are reported with respect to a 2000 CE baseline. Over a 150 year time horizon, the semi-empirical projections under RCP 2.6 (49 (27–87) cm) compare moderately well to the process-based estimates of Kopp *et al* (2014) (70 (30–150) cm) and to the set of Kopp *et al* (2017) projections that include Antarctic ice-shelf hydrofracturing and ice-cliff collapse mechanisms (87 (39–152) cm). Median semi-empirical projections are moderately lower than the process-based estimates, and the high-end tail notably thinner.

Over longer time periods, the differences between semi-empirical and process-based projections become more acute. Levermann *et al* (2013) reported a median GMSL rise of 2.3 m °C^{-1} over 2000 years, with a 66% credible interval of 1.0–4.9 m °C^{-1}. In the semi-empirical model, applying a stepwise warming of 1 °C

Figure 1. Temperature scenarios that meet the goals of the Paris Agreement (top row) and corresponding projections of the amount (middle row) and rate (bottom row) of global mean sea-level (GMSL) rise generated using a semi-empirical model. Historical temperature data is Cowtan and Way (2014). Historical global mean sea-level data are from Hay *et al* (2015) (black), Dangendorf *et al* (2017) (red) and Church and White (2011) (blue). The historical rates were calculated from singular spectrum analysis-filtered (Moore *et al* 2005) GMSL data. The gray bands in the second and third row show the 90% credible interval of the semi-empirical calibration. Within each column of panels, the colored scenarios correspond to one another. Shaded green and yellow envelopes represent the 5%–95% uncertainty of the most extreme scenarios. See also table 1.

from a pre-industrial climate state (mean 1850–1879 CE) for 2000 years yields only 0.8 m °C^{-1} with a 66% credible interval of 0.5–1.3 m °C^{-1}. This discrepancy is one motivation for limiting the use of the semi-empirical model to a 150 year timescale.

Temperature scenarios

Scenarios of future temperature change compared to a baseline period are necessary to generate GMSL projections using a semi-empirical model. However, few existing emissions scenarios result in warming being held at (or below) 2 °C. Therefore, we generated scenarios of future temperature change using two approaches: (1) defining single-temperature trajectories of different forms, and (2) sub-sampling temperature projections generated under RCP 2.6. The scenarios in the first approach exhibit a spread that corresponds to different policy targets with a single climate sensitivity, whereas the spread of temperature projections from the second approach represent a single emissions pathway (policy target), but an uncertain climate response.

Prescribing single-temperature trajectories, as in our first approach, skips the steps that are necessary to transform greenhouse gas emissions into corresponding temperature change with associated uncertainty. It is an idealized approach because societal decisions

directly affect emissions of climate forcers but only indirectly affect temperature. Nevertheless, it is a valid approach to explore possible GMSL outcomes and reflects the Paris Agreement's primary focus on temperature limits. The Paris Agreement also includes a goal of net-zero greenhouse gas emissions in the second half of the century, which is consistent with the RCP 2.6 based projections used in our second approach.

In our first approach, we employ two different shapes of idealized temperature trajectories resulting in a 1.5 °C–2.0 °C increase in global mean surface temperature by 2150 CE. (1) The 'stabilization' trajectories follow a simple Gaussian rise that stabilizes at its peak. They are characterized by reaching the temperature limit from below. (2) The 'overshoot' trajectories are linear combinations of a Gaussian curve and an error function. In this trajectory, global mean surface temperature initially exceeds the long-term goal before cooling to reach the limit from above. Both types of trajectory begin in 2000 CE with an average rate of warming over the period 1985–2015 CE of ~0.2 °C decade^{-1} (Cowtan and Way 2014). The six different stabilization scenarios (figure 1(*A*) reach their peak temperatures of 1.5 °C–2.0 °C in 2050 CE. The six overshoot scenarios (figure 1(*D*) stabilize at 1.5 °C and vary the magnitude of overshoot from 0 °C–0.5 °C (the zero overshoot equals the 1.5 °C stabilization scenario), with the timing of peak warmth fixed at 2050 CE.

Table 1. The amount and rate of global mean sea-level rise scenarios, expressed in cm relative to 2000 CE, projected under different temperature trajectories in 2050, 2100 and 2150 CE. See also figure 1.

Year of projection	Temperature scenario	GMST	GMSL (cm)	GMSL rate (mm yr^{-1})
2050 CE	Stab 1.5 in 2050 CE	1.50 °C	19 (15–24)	4.4 (3.4–5.3)
	Stab 2.0 in 2050 CE	2.00 °C	24 (19–31)	6.2 (4.9–7.8)
	Os 2.0 in 2050 CE	2.00 °C	24 (19–31)	6.2 (4.9–7.8)
2100 CE	Stab 1.5 in 2050 CE	1.50 °C	37 (29–46)	2.9 (1.8–4.3)
	Stab 2.0 in 2050 CE	2.00 °C	50 (39–61)	4.2 (2.8–5.9)
	Os 2.0 in 2050 CE	1.53 °C	44 (34–55)	2.5 (0.9–4.1)
2150 CE	Stab 1.5 in 2050 CE	1.50 °C	49 (36–65)	2.0 (0.9–3.7)
	Stab 2.0 in 2050 CE	2.00 °C	67 (50–86)	2.9 (1.3–5.0)
	Os 2.0 in 2050 CE	1.50 °C	54 (39–72)	1.7 (0.4–3.5)

An additional six stabilization scenarios (the 2 °C stabilization scenarios) fix the magnitude of warming at 2 °C, but vary the timing of peak warmth from 2030–2080 CE (figure 1(G)).

In our second approach, RCP 2.6 temperature projections were generated as in Kopp *et al* (2016a), from the prescribed radiative forcing using the simple climate model MAGICC6 (Meinshausen *et al* 2011). To assess the consequences of achieving the 1.5 °C stabilization temperature with different probabilities, we subsampled the temperature realizations by randomly dropping realizations that exceeded the 1.5 °C limit until a subset was obtained that achieved a specific likelihood of not exceeding this limit. In the stabilized subsamples, no exceedance of 1.5 °C at any point prior to 2150 CE was allowed, while in the overshoot subsamples, overshooting 1.5 °C was allowed if the temperature returned to, or fell below, this limit by 2150 CE. We repeated the sampling process ten times to achieve convergence. In the remainder of the text and figures, we refer to these temperature scenarios as subsampled RCPs (sRCPs), which are labeled based on the temperature limit and the likelihood that it is met. For example, the sRCP 1.5 70% scenario describes a subsample of RCP 2.6 with a 70% probability that global mean surface temperature increase does not exceed 1.5 °C. For comparison, we also project GMSL using all the temperature projections associated with RCP 2.6.

The advantage of the sRCP method is that we specify exactly the probability of exceeding the temperature limit and compare GMSL projections under circumstances yielding a desired tolerable probability of exceeding 1.5 °C. However, this tolerable probability is not achieved by altering emissions trajectories, but instead by effectively trimming climate sensitivity to achieve the desired result. This approach provides a workaround for the absence of a RCP more fully consistent with the Paris Agreement's 1.5 °C target.

Global mean sea-level projections

Under the 'stabilization' temperature scenarios, the amount and rate of GMSL rise varies in accordance with the temperature reached (figure 1(A), (B) and (C), table 1). Stabilizing global mean surface temperature

at 1.5 °C in 2050 CE yields a GMSL rise of 49 (36–65) cm by 2150 CE. The peak rate of GMSL rise is 4.5 (3.6–5.6) mm yr^{-1}, reached by 2041 CE (2017–2087) CE, and decreases to 2.0 (0.9–3.7) mm yr^{-1} by 2150 CE. Stabilizing temperature in 2050 CE at 2 °C yields 67 (50–86) cm of GMSL rise by 2150 CE, with a peak rate of 6.3 (5.1–8.1) mm yr^{-1}, reached by 2044 (2024–2079) CE, declining to 2.9 (1.3–5.0) mm yr^{-1} in 2150 CE. The difference among scenarios is small before ∼2050 CE, but considerable by 2150 CE (figure 2(A), (B) and (C)). A difference in peak temperature of 0.5 °C yields a maximum difference in the rate of GMSL rise of 1.9 (1.4–2.6) mm yr^{-1} in 2047 (2031–2074) CE, which for comparison is likely more than the observed 20th century rate of GMSL rise (median estimates of 1.3–1.9 mm yr^{-1}) (Church and White 2011, Dangendorf *et al* 2017, Hay *et al* 2015, Jevrejeva *et al* 2014, Ray and Douglas 2011, Thompson *et al* 2016, Wenzel and Schröter 2014). Following temperature stabilization, this difference diminishes to 0.8 (0.4–1.3) mm yr^{-1} in 2150 CE. The difference of GMSL in 2150 CE is 17 (14–21) cm. By 2100 CE, the semi-empirical projections are in good agreement with the projections of Schleussner *et al* (2016), who scaled different sea-level contributors with modeled temperature and ocean heat uptake. Our median GMSL rise with a 66% credible interval for 1.5 °C and 2 °C stabilization are 37 (31–43) cm and 50 (43–56) cm, respectively, while Schleussner *et al* (2016) reported 40 (30–55) cm and 50 (35–65) cm. One reason for the broader uncertainty ranges of Schleussner *et al* (2016) is that the temperatures they use for projecting GMSL have an uncertainty range and only reach 1.5 °C and 2 °C with a 50% probability.

In scenarios where the magnitude of overshoot is varied with a fixed timing (2050 CE) and the long-term goal of 1.5 °C, the amount of GMSL rise is proportional to the amount of overshoot (figures 1(D)−(F), table 1). The amount of GMSL rise and its rate before 2050 CE is the same as projections generated under the stabilization scenario. The convergence to lower temperatures after peaking brings a reduction in GMSL rise and its rate only in the long term (figures 2(H) and (I)). For example, reaching a peak temperature of 2 °C in 2050 CE before a subsequent convergence to 1.5 °C results in a 54 (39–72) cm GMSL rise at a rate of 1.7 (0.4–3.5) mm yr^{-1} in 2150 CE, with the highest rates of rise, 6.3 (5.1–8.1) mm yr^{-1}, reached in 2044 (2024–2063) CE.
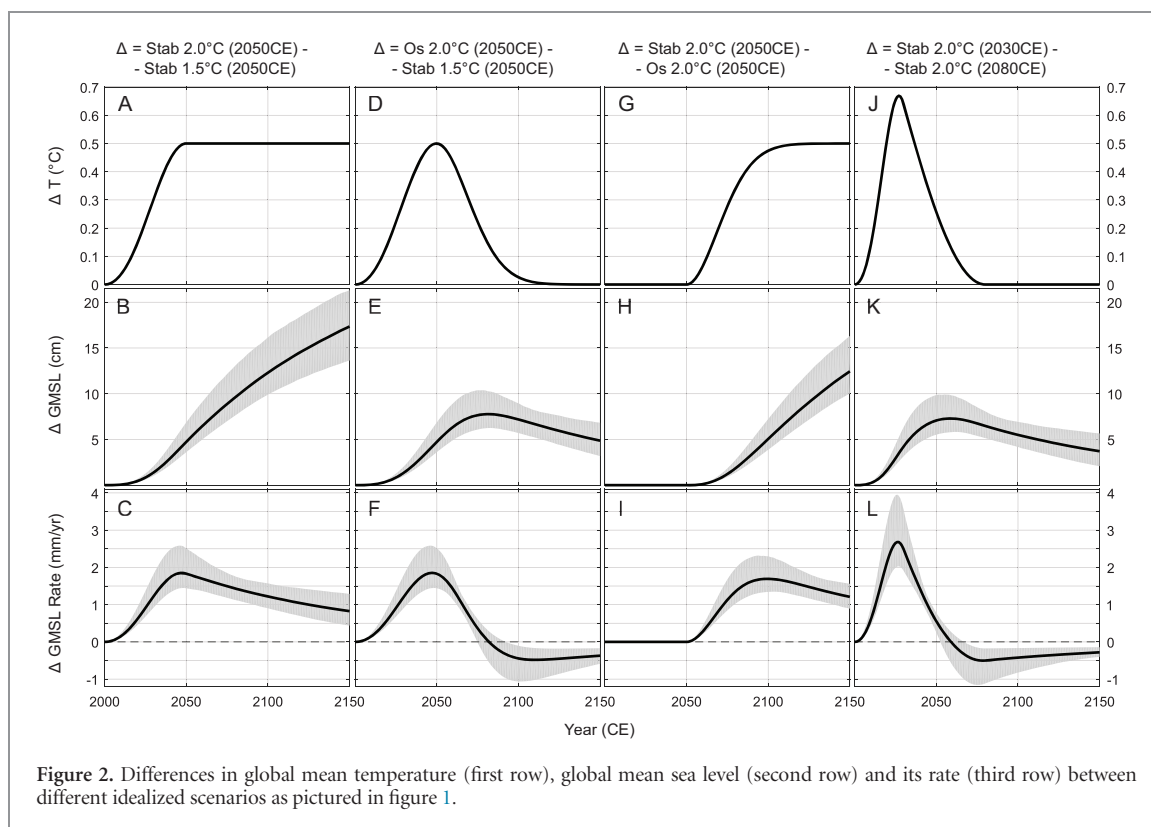
Figure 2. Differences in global mean temperature (first row), global mean sea level (second row) and its rate (third row) between different idealized scenarios as pictured in figure 1.

The 2 °C overshoot scenario with subsequent stabilization at 1.5 °C yields up to 1.9 (1.4–2.6) mm yr^{-1} (in 2047 (2031–2059) CE) higher rates and 8 (6–10) cm (in 2081 (2054–2119) CE) higher GMSL than a 1.5 °C stabilization without overshoot (figures 2(D)−(F)). By 2150 CE, GMSL in the 2 °C overshoot scenario is 5 (3–7) cm higher, but the rate of rise is 0.4 (0.2–0.6) mm yr^{-1} smaller than in the 1.5 °C stabilization scenario, due to the rapid temperature drop after reaching 2 °C in 2050 CE. Compared to a 2 °C stabilization scenario, a subsequent decline to 1.5 °C after peaking at 2 °C lowers GMSL in 2150 CE by 12 (10–16) cm and its rate by 1.2 (0.9–1.6) mm yr^{-1} (figures 2(G)−(I)).

In the six scenarios where temperatures stabilize at 2 °C and at different times from 2030 CE to 2080 CE, there is little difference in the amount of GMSL rise by 2150 CE (4 (2–6) cm) between the 2030 CE and 2080 CE peak scenarios, but there is marked difference in the maximum rate of GMSL rise that is achieved (figures 2(J)−(L)). An earlier peaking at the same temperature leaves less time to reach this temperature and thus causes a faster warming and a higher maximum rate of GMSL rise. Peaking at 2 °C in 2080 CE rather than 2030 CE yields a decrease in the rate of GMSL rise of up to 2.7 (2.0–4.0) mm yr^{-1} in 2026 (2018–2034) CE while delaying the peaks of GMSL rate from 2028 (2017–2053) CE to 2063 (2029–2122) CE.

Many of the principal results from the idealized temperature stabilization and overshoot scenarios are also apparent in the GMSL projections generated from the sRCPs (figure 3, table 2). At 2050 CE, there is relatively little difference in the amount of GMSL rise

predicted for the suite of sRCPs. In contrast, the differences at 2100 CE and 2150 CE are considerable. In 2150 CE, increasing the likelihood of not exceeding 1.5 °C from 46% (RCP 2.6) to 95% (without transient overshoot) lowers GMSL rise from 49 (27−87) cm to 38 (25−58) cm. If temperature can transiently overshoot 1.5 °C, but stays below this threshold by 2150 CE, then GMSL is lowered to 41 (25−64) cm.

Discussion

Projections from our semi-empirical model show that amount and rate of future GMSL rise is dependent upon temperature scenarios, even where the scenarios under investigation meet the ambitious goals of the Paris Agreement. Subsampling RCP 2.6 to lower the likelihood of exceeding 1.5 °C by 2150 CE from 54% to 5%, without overshoot, makes a ∼10 cm difference in the median GMSL projection. Under the idealized trajectories, stabilizing temperature at 1.5 °C above pre-industrial results in a GMSL change that is smaller (by 17 (14–21) cm in 2150) and slower (for the maximum rate, by 1.9 (1.4–2.6) mm yr^{-1}) than stabilization at 2.0 °C. An overshoot to 2 °C and a subsequent decline to 1.5 °C also causes less GMSL rise (12 (10–16) cm) by 2150 CE than stabilization at 2 °C. If stabilization at 2 °C occurred in 2080 CE, then the maximum rate of GMSL rise is 2.6 (2.0–4.0) mm yr^{-1} slower than if temperature were to stabilize in 2030 CE. These results indicate that an immediate reduction in the rate of warming and a low stabilization
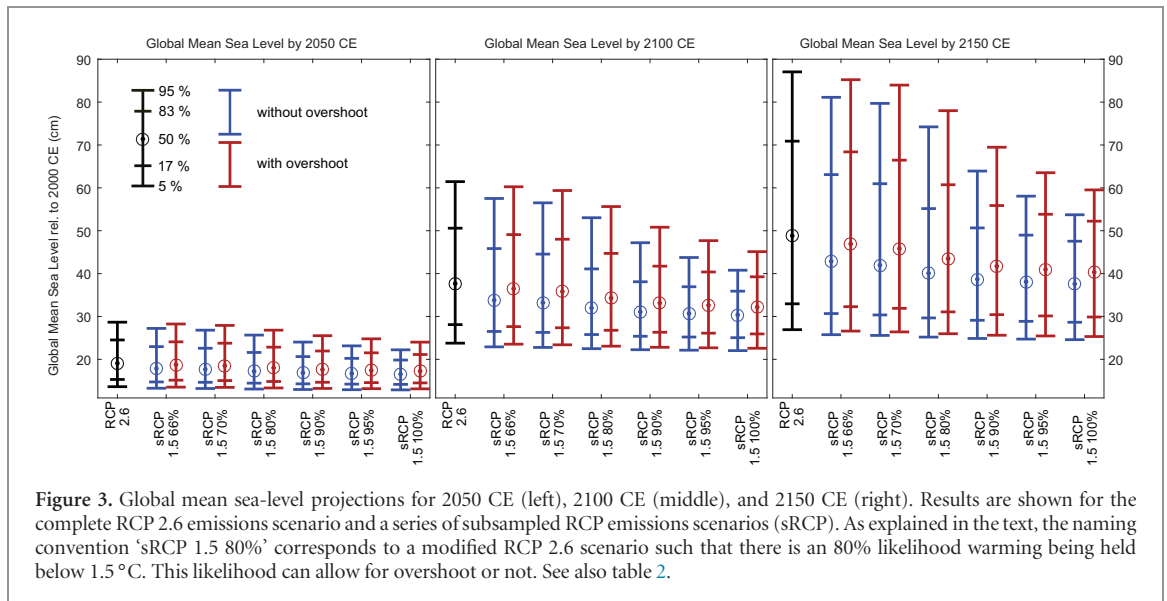
Figure 3. Global mean sea-level projections for 2050 CE (left), 2100 CE (middle), and 2150 CE (right). Results are shown for the complete RCP 2.6 emissions scenario and a series of subsampled RCP emissions scenarios (sRCP). As explained in the text, the naming convention 'sRCP 1.5 80%' corresponds to a modified RCP 2.6 scenario such that there is an 80% likelihood warming being held below 1.5 °C. This likelihood can allow for overshoot or not. See also table 2.

Table 2. Global mean sea-level projections for different years and temperature scenarios expressed in cm relative to 2000 CE. As explained in the text, 'sRCP 1.5 95%' is a subsampled RCP 2.6 scenario such that there is an 95% likelihood that warming is being held below 1.5 °C. This likelihood can be calculated allowing for overshoot or not. See also figure 3.

Year of projection	Temperature scenario	GMSL without overshoot (cm)	GMSL with overshoot (cm)
2050 CE	RCP 2.6	19 (14–29)	19 (14–29)
	sRCP 1.5 95%	17 (13–23)	17 (13–25)
2100 CE	RCP 2.6	38 (24–61)	38 (24–61)
	sRCP 1.5 95%	31 (22–44)	33 (23–48)
2150 CE	RCP 2.6	49 (27–87)	49 (27–87)
	sRCP 1.5 95%	38 (25–58)	41 (25–64)

temperature, even if overshot transiently, will result in a considerable reduction in the amount and rate of GMSL rise that global coastlines and coastal communities will experience during the 21st century and beyond.

Despite the low temperature scenarios and the short time frame considered here, our projections are likely to be underestimates, because the processes driving GMSL change in future may differ substantially from those in the calibration period (Joughin *et al* 2014, Rignot *et al* 2014). The relatively rapid decline in the rate of GMSL change after temperature stabilization is a direct consequence of our calibrated response time scale of 138 (64−366) years, which could be an underestimation because the temperature variability during the model's calibration period is shorter than the expected full equilibration time. Compared to the process-based projections of Kopp *et al* (2017), we underestimate the projected high-end, 95th percentile tail of sea-level rise under RCP 2.6 in 2150 by about 75%.

Semi-empirical projections such as those presented here do not take into account local and regional factors that can cause relative sea level change to differ markedly from GMSL change. These factors include local land motion, the gravitational, rotational, and deformational effects of redistributing mass between the cryosphere and the ocean, and the redistribution of existing ocean mass by ocean and atmospheric

circulation (Mitrovica *et al* 2011, Yin *et al* 2010, Kopp *et al* 2015). Coastal planning needs to account for these factors, not just GMSL change (Hinkel *et al* 2015). Complementary approaches to projecting local sea-level changes (e.g. Kopp *et al* 2014, Nicholls *et al* 2014, Perrette *et al* 2013, Slangen *et al* 2014) and estimating the local sea-level effects of different temperature targets (e.g. Rasmussen *et al* 2017, Schleussner *et al* 2016) can be useful in this regard.

Nevertheless, the differences among scenarios in rates of GMSL rise and the timing of their peaks is an important, if less localized, indicator of consequences for tidal flooding (Sweet and Park 2014), shoreline changes (Stive 2004, Zhang *et al* 2004), and ecological change. For example, salt marshes and mangroves can be drowned if the local rate of relative sea-level rise exceeds their ecological ability to maintain their position in the tidal frame through sediment accumulation (Kirwan *et al* 2010). The difference in peak rates of rise between scenarios is sufficiently large that it could represent the difference between drowning and survival for some ecosystems. This is one reason why in its 2006 report the German governmental advisory board for global environmental changes (WBGU) proposed a guardrail limit for the rate of GMSL rise of 5 mm yr^{-1} (Schubert *et al* 2006). Our results indicate that this guardrail could be exceeded even if warming is held below 2 °C. In contrast, the corresponding

guardrail limit for total GMSL rise of 1 m is unlikely to be exceeded before 2150 CE if warming is held below 2 °C.

Methods

The semi-empirical model follows Kopp *et al* (2016a) and has the following form:

$$\mathrm{d}h\,(t)/\mathrm{d}t = a\left(T\,(t) - T_0\,(t)\right) + c\,(t) \quad \text{with}$$

$$\mathrm{d}T_0\,(t)/\mathrm{d}t = T\,(t) - T_0\,(t)/\tau$$

$$\mathrm{d}c\,(t)/\mathrm{d}t = -c/\tau_c.$$

In this model, the rate of sea-level change (dh/dt) equals the temperature change above an equilibrium temperature (T-T_0) times the sensitivity a plus a decaying rate c. The equilibrium temperature T_0 decays towards T on the timescale τ while c decays on the timescale τ_c. The final parameter sample size is 1000 and the parameter's median values with 90% uncertainties are given in table SI1.

As described in Kopp *et al* (2016a), the model is calibrated with the Common Era GMSL curve of Kopp *et al* (2016a) and two long-term temperature records (Mann *et al* 2009, Marcott *et al* 2013). The GMSL curve of Kopp *et al* (2016a) spans the past 3000 years and was generated using a spatio-temporal statistical analysis of relative sea-level reconstructions generated from coastal sediment, coral microatolls and archaeological remains that were combined with instrumental relative sea-level records from a global network of tide gauges. See Kopp *et al* (2016a) for more details. Differences in sea-level projections among scenarios were calculated for each of the 1000 semi-empirical model parameter sets separately; the percentiles using each of the two calibration data sets were calculated and then combined by taking the mean of their medians and the extrema of their uncertainty envelope.

The stabilization and overshoot temperature trajectories are described by the following equations:

$$T_{\text{stabilization}}(t) =$$

$$\begin{cases} h\,\exp(-(t - t_0)^2/2\sigma^2) & \text{for } t \leqslant t_0 \\ h & \text{for } t > t_0 \end{cases}$$

$$T_{\text{overshoot}}(t) =$$

$$\begin{cases} h\,\exp(-(t - t_0)^2/2\sigma^2) & \text{for } t \leq t_0 \\ h_1\,\exp(-(t - t'_0)^2/2\sigma'^2) + \\ h_2(1 + \mathrm{erf}\,(t - t'_0)/\sqrt{2}\sigma') & \text{for } t > t_0. \end{cases}$$

The parameters h, h_1, h_2, t_0, t'_0, σ and σ' were set at different values to generate the stabilization and overshoot scenarios. For all these scenarios, the initial rate of temperature rise in 2000 CE is set to be the mean rate of the second GMST version of Cowtan and Way (2014) (CW) between 1985 and 2015 CE ($\sim$0.2 °C decade^{-1}).

The scenarios start in 2000 CE at the mean CW temperature for 1985–2015 CE. The warming above the pre-industrial level, taken as 1850–1879 CE, that had already happened to this point was calculated from CW (0.72 °C) and subtracted from the temperature target of the scenario.

The subsampled RCPs (sRCPs) were subsampled from RCP 2.6 driven temperature projections, calculated using the simple climate model MAGICC6 (Meinshausen *et al* 2011) in probabilistic mode as in Rasmussen *et al* (2017). This resulted in 600 temperature trajectories $\left(T_i^{\text{RCP2.6}}\right)$, which we expressed as anomalies with respect to their 1971–2000 CE means. The temperature change between 1850−1879 CE (pre-industrial) and 1971–2000 CE was again calculated from CW. The criteria for staying below 1.5 °C for a certain trajectory $T_i^{\text{RCP2.6}}$ were max $\left(T_i^{\text{RCP2.6}}\right) \leq 1.5°C$ if overshoot was not allowed and $T_i^{\text{RCP2.6}}\,(2150CE) \leq 1.5°C$ if overshoot was allowed. To ensure a certain probability of staying below the 1.5 °C, we omitted a fraction of $T_i^{\text{RCP2.6}}$ that did not meet the selected criterion.

The use of a simulation's 1971−2000 CE period as a reference level, with a fixed adjustment for the difference between this reference period and the pre-industrial baseline, has a significant influence on the assessment of whether a simulation meets a criterion (table SI2). Of our RCP 2.6 simulations, 54% exceed 1.5 °C using the no-overshoot criterion as described above. This falls to 42% if, instead of using each simulation's 1971−2000 CE as a reference level and then adjust to the pre-industrial reference level using CW, we use each simulation's 1850−1879 CE as a reference level. As a comparison, Schurer *et al* (2017) estimated a 61% probability that RCP 2.6 would exceed 1.5 °C when using a late-nineteenth century reference level for the pre-industrial.

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References

Ablain M, Legeais J F, Prandi P, Marcos M, Fenoglio-Marc L, Dieng H B, Benveniste J and Cazenave A 2017 Satellite altimetry-based sea level at global and regional scales *Surv. Geophys.* **38** 7–31

Bassis J N and Walker C C 2011 Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice *Proc. R. Soc.* A **468** 913–31

Bittermann K, Rahmstorf S, Perrette M and Vermeer M 2013 Predictability of twentieth century sea-level rise from past data *Environ. Res. Lett.* **8** 014013

Cazenave A, Dieng H-B, Meyssignac B, von Schuckmann K, Decharme B and Berthier E 2014 The rate of sea-level rise *Nat. Clim. Change* **4** 358–61

Chen X, Zhang X, Church J A, Watson C S, King M A, Monselesan D, Legresy B and Harig C 2017 The increasing rate of global mean sea-level rise during 1993–2014 *Nat. Clim. Change* **7** 492–5

Church J A and White N J 2011 Sea-level rise from the late 19th to the early 21st century *Surv. Geophys.* **32** 585–602

Clark P U *et al* 2016 Consequences of twenty-first-century policy for multi-millennial climate and sea-level change *Nat. Clim. Change* **6** 360–9

Church J A *et al* 2013 Sea level change *Climate Change 2013: The Physical Science Basis* ed Stocker T F *et al* (Cambridge: Cambridge University Press) pp 1137–1216

Cowtan K and Way R G 2014 Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends: coverage bias in the HadCRUT4 temperature series *Q. J. R. Meteorol. Soc.* **140** 1935–44

Dangendorf S, Marcos M, Wöppelmann G, Conrad C P, Frederikse T and Riva R 2017 Reassessment of 20th century global mean sea level rise *Proc. Natl Acad. Sci.* **114** 5946–51

DeConto R M and Pollard D 2016 Contribution of Antarctica to past and future sea-level rise *Nature* **531** 591–7

Dieng H B, Cazenave A, Meyssignac B and Ablain M 2017 New estimate of the current rate of sea level rise from a sea level budget approach *Geophys. Res. Lett.* **44** 3744–51

Figueres C, Schellnhuber H J, Whiteman G, Rockström J, Hobley A and Rahmstorf S 2017 Three years to safeguard our climate *Nat. News* **546** 593

Garner A J, Mann M E, Emanuel K A, Kopp R E, Lin N, Alley R B, Horton B P, DeConto R M, Donnelly J P and Pollard D 2017 Impact of climate change on New York City's coastal flood hazard: increasing flood heights from the preindustrial to 2300 CE *Proc. Natl Acad. Sci.* **114** 11861–6

Gornitz V, Lebedeff S and Hansen J 1982 Global sea level trend in the past century *Science* **215** 1611

Grinsted A, Moore J C and Jevrejeva S 2009 Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD *Clim. Dyn.* **34** 461–72

Hauer M E 2017 Migration induced by sea-level rise could reshape the US population landscape *Nat. Clim. Change* **7** 321–5

Hay C C, Morrow E, Kopp R E and Mitrovica J X 2015 Probabilistic reanalysis of twentieth-century sea-level rise *Nature* **517** 481–4

Hinkel J, Jaeger C, Nicholls R J, Lowe J, Renn O and Peijun S 2015 Sea-level rise scenarios and coastal risk management *Nat. Clim. Change* **5** 188–90

Jevrejeva S, Grinsted A and Moore J C 2009 Anthropogenic forcing dominates sea level rise since 1850 *Geophys. Res. Lett.* **36** L20706

Jevrejeva S, Moore J C, Grinsted A, Matthews A P and Spada G 2014 Trends and acceleration in global and regional sea levels since 1807 *Glob. Planet. Change* **113** 11–22

Joughin I, Smith B E and Medley B 2014 Marine ice sheet collapse potentially under way for the Thwaites Glacier basin, West Antarctica *Science* **344** 735

Kirwan M L, Guntenspergen G R, D'Alpaos A, Morris J T, Mudd S M and Temmerman S 2010 Limits on the adaptability of coastal marshes to rising sea level *Geophys. Res. Lett.* **37** L23401

Kopp R E, DeConto R M, Bader D A, Horton R M, Hay C C, Kulp S, Oppenheimer M, Pollard D and Strauss B H 2017 Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections *Earth's Future* (arXiv:1704.05597)

Kopp R E, Hay C C, Little C M and Mitrovica J X 2015 Geographic variability of sea-level change *Curr. Clim. Change Rep.* **1** 192–204

Kopp R E, Horton R M, Little C M, Mitrovica J X, Oppenheimer M, Rasmussen D J, Strauss B H and Tebaldi C 2014 Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites *Earth's Future* **2** 383–406

Kopp R E, Kemp A C, Bittermann K, Horton B P, Donnelly J P, Gehrels W R, Hay C C, Mitrovica J X, Morrow E D and Rahmstorf S 2016a Temperature-driven global sea-level variability in the Common Era *Proc. Natl Acad. Sci.* **113** E1434–41

Kopp R E, Shwom R, Wagner G and Yuan J 2016b Tipping elements and climate-economic shocks: pathways toward integrated assessment *Earth's Future* **4** 346–72

Levermann A, Clark P U, Marzeion B, Milne G A, Pollard D, Radic V and Robinson A 2013 The multimillennial sea-level commitment of global warming *Proc. Natl Acad. Sci.* **110** 13745–50

Lichter M, Vafeidis A T, Nicholls R J and Kaiser G 2010 Exploring data-related uncertainties in analyses of land area and population in the 'low-elevation coastal zone' (LECZ) *J. Coast. Res.* **27** 757–68

Mann M E, Zhang Z, Rutherford S, Bradley R S, Hughes M K, Shindell D, Ammann C, Faluvegi G and Ni F 2009 Global signatures and dynamical origins of the Little Ice Age and medieval climate anomaly *Science* **326** 1256–60

Marcott S A, Shakun J D, Clark P U and Mix A C 2013 A reconstruction of regional and global temperature for the past 11 300 years *Science* **339** 1198–201

Marzeion B and Levermann A 2014 Loss of cultural world heritage and currently inhabited places to sea-level rise *Environ. Res. Lett.* **9** 034001

Meinshausen M, Raper S C B and Wigley T M L 2011 Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—part 1: model description and calibration *Atmos. Chem. Phys.* **11** 1417–56

Mitrovica J X, Gomez N, Morrow E, Hay C, Latychev K and Tamisiea M E 2011 On the robustness of predictions of sea level fingerprints *Geophys. J. Int.* **187** 729–42

Moftakhari H R, Salvadori G, AghaKouchak A, Sanders B F and Matthew R A 2017 Compounding effects of sea level rise and fluvial flooding *Proc. Natl Acad. Sci.* **114** 9785–90

Moore J C, Grinsted A and Jevrejeva S 2005 New tools for analyzing time series relationships and trends *Eos. Trans. Am. Geophys. Union* **86** 226–32

Moss R H *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56

Nicholls R J, Hanson S E, Lowe J A, Warrick R A, Lu X and Long A J 2014 Sea-level scenarios for evaluating coastal impacts: sea-level scenarios for evaluating coastal impacts *Wiley Interdiscip. Rev. Clim. Change* **5** 129–50

Nicholls R J, Marinova N, Lowe J A, Brown S, Vellinga P, de Gusmao D, Hinkel J and Tol R S J 2011 Sea-level rise and its possible impacts given a beyond 4 °C world in the twenty-first century. *Phil. Trans. R. Soc.* A **369** 161–81

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 Syst. Dyn.* **4** 11–29

Pollard D, DeConto R M and Alley R B 2015 Potential Antarctic ice sheet retreat driven by hydrofracturing and ice cliff failure *Earth Planet. Sci. Lett.* **412** 112–21

Rahmstorf S 2017 Rising hazard of storm-surge flooding *Proc. Natl Acad. Sci.* **114** 11806–8

Rahmstorf S 2007 A semi-empirical approach to projecting future sea-level rise *Science* **315** 368

Rasmussen D J, Bittermann K, Buchanan M, Kulp S, Strauss B, Kopp R E and Oppenheimer M 2017 Coastal flood implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd century *Environ. Res. Lett.* submitted (arXiv:1710.08297)

Ray R D and Douglas B C 2011 Experiments in reconstructing twentieth-century sea levels *Prog. Oceanogr.* **91** 496–515

Rignot E, Mouginot J, Morlighem M, Seroussi H and Scheuchl B 2014 Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler Glaciers, West Antarctica, from 1992 to 2011 *Geophys. Res. Lett.* **41** 3502–9

Robinson A, Calov R and Ganopolski A 2012 Multistability and critical thresholds of the Greenland ice sheet *Nat. Clim. Change* **2** 429–32

Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N and Schellnhuber H J 2017 A roadmap for rapid decarbonization *Science* **355** 1269

Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K and Meinshausen M 2016 Paris Agreement climate proposals need a boost to keep warming well below 2 °C *Nature* **534** 631–9

Schleussner C-F *et al* 2016 Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C *Earth Syst. Dyn.* **7** 327–51

Schubert R, Schellnhuber H J, Buchmann N, Epiney A, Griesshammer R, Kulessa M E, Messner D, Rahmstorf S and Schmid J 2006 *Die Zukunft der Meere—zu warm, zu hoch, zu sauer, Sondergutachten* (Berlin: Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen)

Schurer A P, Mann M E, Hawkins E, Tett S F B and Hegerl G C 2017 Importance of the pre-industrial baseline for likelihood of exceeding Paris goals *Nat. Clim. Change* **7** 563–7

Slangen A B A, Carson M, Katsman C A, van de Wal R S W, Köhl A, Vermeersen L L A and Stammer D 2014 Projecting twenty-first century regional sea-level changes *Clim. Change* **124** 317–32

Stive M J F 2004 How important is global warming for coastal erosion? *Clim. Change* **64** 27–39

Sweet W V and Park J 2014 From the extreme to the mean: acceleration and tipping points of coastal inundation from sea level rise *Earth's Future* **2** 579–600

Thompson P R, Hamlington B D, Landerer F W and Adhikari S 2016 Are long tide gauge records in the wrong place to measure global mean sea level rise? *Geophys. Res. Lett.* **43** 10,403–411

United Nations Framework Convention on Climate Change 2015 *Adoption of the Paris Agreement, 21st Conference of the Parties* (Paris: United Nations)

van Vuuren D P *et al* 2012 A proposal for a new scenario framework to support research and assessment in different climate research communities *Glob. Environ. Change* **22** 21–35

Vermeer M and Rahmstorf S 2009 Global sea level linked to global temperature *Proc. Natl Acad. Sci. USA* **106** 21527–32

Wenzel M and Schröter J 2014 Global and regional sea level change during the 20th century *J. Geophys. Res. Oceans* **119** 7493–508

Yin J, Griffies S M and Stouffer R J 2010 Spatial variability of sea level rise in twenty-first century projections *J. Clim.* **23** 4585–607

Zhang K, Douglas B C and Leatherman S P 2004 Global warming and coastal erosion *Clim. Change* **64** 41