Sea-level commitment as a gauge for climate policy

A well-defined relationship between global mean sea-level rise and cumulative carbon emissions can be used to inform policy about emission limits to prevent dangerous and essentially permanent anthropogenic interference with the climate system.

Peter U. Clark, Alan C. Mix, Michael Eby, Anders Levermann, Joeri Rogelj, Alexander Nauels and David J. Wrathall

It is now clear that cumulative emissions of CO_2 control the magnitude of long-term warming[1,2], while the rate of warming is modulated by the emissions pathway[3], facilitating the identification of emissions quotas that would limit global warming to a temperature target mandated by climate policy[4]. This framework forms the cornerstone of the Paris Agreement adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), which aims to hold "the increase in the 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" by providing the means to both quantify the allowable budget of remaining emissions required to achieve the treaty goals[4] and assess the implications of emissions-reduction pledges made by countries[5].

Although temperature has been used as the main indicator to gauge the long-standing UNFCCC goal of avoiding "dangerous anthropogenic interference with the climate system"[6], we argue that global mean sea-level rise (GMSLR) would be a useful additional measure for setting emissions quotas to achieve this objective[7]. The enormous socio-economic and ecological impacts of GMSLR and sea-level extremes during the twenty-first century are well known[8]. Coastal submergence from SLR and the corresponding increase in the frequency and intensity of sea-level extremes will irreversibly affect the distribution of a large fraction of the human population[8–10]. Forty per cent of the global population (nearly three billion people) reside within 100 km of the coast. Much of that population is concentrated in megacities and on fertile low-lying floodplains, river deltas and islands — areas that are at high risk of impacts from GMSLR. The United States reflects this tendency, with roughly 50% of the population in coastal counties[9]. Increasing population density along coastal zones in the coming decades to centuries will exacerbate these problems[11].

In the absence of effective mitigation, GMSLR will accelerate over the coming centuries, and will continue for millennia[10,12]. Persistent long-term SLR will increase the frequency and amplitude of sea-level extremes. Because extreme events occur on such short timescales, they will be among the most disruptive mechanisms of coastal inundation, and their effects are already manifesting themselves through increased coastal flooding[13,14]. This increase in sea-level extremes will be an early driver of sudden, large-scale, permanent displacement and migration that expands the socio-economic impacts of SLR beyond the coastal zone to locations where migrants will require jobs, housing, healthcare, schools and other services[9]. With no adaptation, economic losses in large coastal cities due to coastal flooding are estimated to grow from US$6 billion annually in 2005 Common Era (CE) to US$1 trillion by 2050 CE[15]. These losses can be reduced to US$60–63 billion through construction of coastal defenses[15], but such well-intended, short-term efforts neglect the long-term horizon of SLR, and thus may increase long-term risks by encouraging coastal development — effectively committing future resources to further defensive measures as sea level continues to rise.

Using cumulative carbon emissions to project GMSLR offers the same advantages as using temperature, as this approach combines the uncertainties associated with climate sensitivity and carbon cycle feedbacks[2]. Like temperature, SLR will occur across the planet unevenly, with departures of >20% from GMSLR possible[16]. The physics behind these departures involves the gravitational, deformational and rotational effects of the loss of land ice, and is sufficiently well known that if the land-ice contributions to GMSLR are well constrained, much of the regional rise can be predicted with reasonable accuracy[17]. However, the response time of GMSLR to climate change due to CO_2 emissions is much longer than that of temperature. At least 90% of peak warming in response to an emission is realized in less than a decade[18], so that transient and peak-warming responses to cumulative emissions are similar. In contrast, the sea-level response time ranges from 10^1–10^2 yr for glacier contributions to 10^3 yr for contributions from deep-ocean warming and ice-sheet melting (if triggered, ice-sheet dynamics may shorten this response). GMSLR from these combined contributions thus continues for many millennia[10]. For this reason, any proportionality between GMLSR and cumulative emissions is transient, and that relationship will evolve over long timescales.

We use published results[10,19] to derive an illustrative example of the relationship of transient sea-level response to cumulative carbon emissions released since the pre-industrial period (1750 CE) for several future time points (Fig. 1). All results from Clark and colleagues[10] are for a stipulated equilibrium climate sensitivity (ECS) of 3.5 °C, which is similar to the ensemble mean ECS (3.2 °C) in IPCC AR5, which is derived from multiple comprehensive models[20]. The 1σ uncertainty in model results (Fig. 1) reflects carbon cycle uncertainty. The spread in sea level for the two simulations with the Bern3D-LPX model for the uncertainty in ECS ranging from 1.5 to 4.5 °C (ref. [10]) are shown on the right of Fig. 1b; this range in ECS was assessed as the likely range (66–100% probability) in AR5.

Figure 1 shows that the response of sea level to a given value of cumulative emissions reflects the multimillennial timescale of SLR and corresponding commitment to those emissions. In contrast, at any given time, the increase in sea level with increasing cumulative emissions

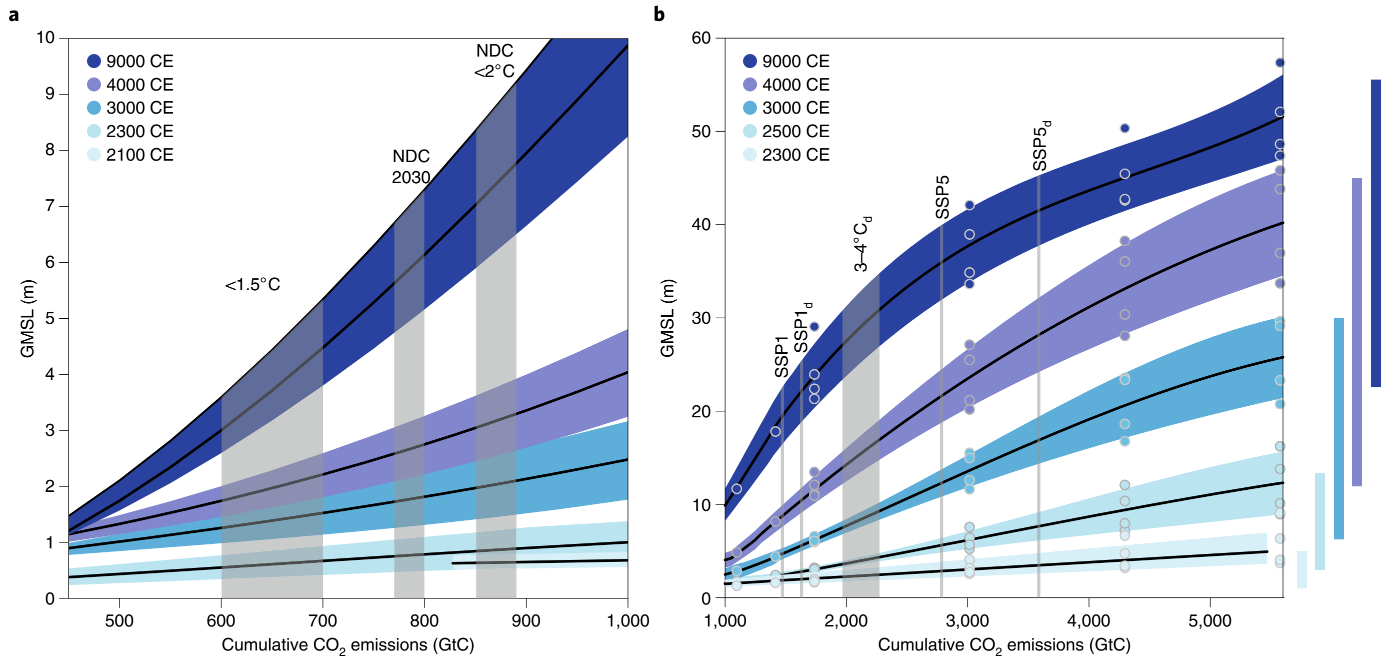

Fig. 1 | GMSL as a function of cumulative carbon emissions. a, GMSL at five future time points for cumulative carbon emissions (relative to the pre-industrial) of between 450 and 1,000 GtC. The 2100 CE scenario is based on four RCPs[19], with cumulative emissions beginning at 830 GtC. The black line and colour envelope represent mean sea level and 1σ uncertainties. The 2300 CE, 3000 CE, 4000 CE and 9000 CE scenarios are from Clark and colleagues[10], with black lines and colour envelopes representing polynomial fits and uncertainty (1σ) to model data from ref. [10]. **b**, GMSL at five future time points for cumulative carbon emissions (relative to the pre-industrial) of between 1,000 and 5,600 GtC. The 2300 CE scenario is based on four RCPs[19], with a maximum value of 5,470 GtC. The black line and colour envelope represent mean sea level and 1σ uncertainty. The 2500 CE, 3000 CE, 4000 CE and 9000 CE scenarios are as shown in **a**; coloured circles represent model results from ref. [10]. Vertical grey bars identify cumulative emissions for several scenarios from the literature (see text and Supplementary Information). Vertical bars to the right of **b** show the spread in GMSLR for the two simulations with the Bern3D-LPX model for uncertainty in ECS values ranging from 1.5 to 4.5 °C (ref. [10]), which the IPCC assessed as the likely range (66–100% probability).

reflects the greater sea-level response to CO_2 forcing[10]. Rising sea level due to thermal expansion varies with the transient profile of emissions, but over multiple centuries and millennia these initial variations become increasingly less important[21]; the signal is then overwhelmed by ice-sheet contributions, with the largest coming from Antarctica[22].

The transient responses calibrated here help to evaluate the long-term implications of cumulative carbon emissions scenarios for sea level (Fig. 1 and Supplementary Information). For example, emissions targets have been identified that can meet the objectives of the Paris Agreement. To this end, signatory countries have agreed to submit so-called nationally determined contributions (NDCs) every five years. A recent estimate of the cumulative CO_2 emissions for the current intended NDCs that cover the period 2000–2030 CE finds a mean value of 324 GtC (310–338 GtC, ±1σ)[23], corresponding to net cumulative emissions of 780 GtC since the pre-industrial (assuming 456 GtC between 1750–1999 CE) (Supplementary Information). From our transient sea-level relationship, this corresponds to a GMSLR of 0.8 m (0.5 to 1.1 m; all uncertainties here ±1σ) at 2300 CE and 5.8 m (4.8 to 6.9 m) at 9000 CE (Fig. 1a and Supplementary Information). We compare this with emission scenarios for the twenty-first century (2005–2100 CE) that would limit warming to 2 °C with current NDC pledges, and scenarios that would cause warming to remain below or exceed 2 °C[5]. The <2°C scenario with currently pledged NDCs (NDC <2°C) and historic emissions (assuming 498 GtC between 1750–2004 CE) would result in 0.9 m (0.5 to 1.2 m) at 2300 CE and 7.4 m (6.0 to 8.8 m) at 9000 CE, whereas the <1.5°C scenario would result in 0.6 m (0.4 to 0.9 m) at 2300 CE and 3.7 m (2.8 to 4.7 m) at 9000 CE (Fig. 1a and Supplementary Information). Thus, even if we successfully limit temperature changes, the long-term sea-level impacts may argue for more restrictive emission quotas during the twenty-first century, continued reductions in quotas beyond the twenty-first century or other long-term policies to mitigate or adapt to continuing SLR.

We also evaluate the implications of carbon emissions associated with the five baseline quantifications of the Shared Socioeconomic Pathways (SSPs)[24]. The baseline SSPs represent quantifications of five narratives on possible trajectories for human development and global environmental changes, barring climate change mitigation beyond what is in place today. Scenarios range from green growth and environmental sustainability (SSP1) to intensive energy and resource development (SSP5)[24]. Some of these scenarios will be used in a framework with the Representative Concentration Pathways to drive climate projections under Phase 6 of the Coupled Model Intercomparison Project for the forthcoming IPCC assessments. None of the baseline SSP CO_2 emissions scenarios reach zero by 2100 CE, so cumulative emissions and the associated committed SLR derived from them are minimum estimates (Supplementary Information). We also consider a hypothetical mitigation scenario by extending the baseline CO_2 emissions down to zero by 2155 CE (see Supplementary Information for details), thus providing a finite and likely minimum value of cumulative carbon emissions for evaluating implications of the baseline SSPs to SLR. The baseline SSP5 scenario with our declining extension has the highest cumulative carbon emissions of the scenarios evaluated here

(3,596 GtC, including historic emissions), leading to GMSLR of 3.7 m (2.7 to 4.8 m) by 2300 CE and 41.6 m (37.8 to 45.3 m) by 9000 CE (Fig. 1b and Supplementary Information). Following scenarios that limit warming to 1.5 °C or 2 °C would strongly limit these GMSLR projections, but far from eliminate the risks (Fig. 1a).

The relationship between cumulative carbon emissions and GMSLR developed here is based on a small number of models. Refinements will require more process studies and modelling to better quantify the uncertainties in the relationships that arise from ice-sheet feedbacks on climate, ice-sheet dynamics and long-term carbon cycle changes. Moreover, mitigation scenarios that limit global mean temperature rise to 1.5 °C or 2 °C are often associated with negative emissions in the latter part of the twenty-first century (Supplementary Information)[5]. It is likely that committed SLR for these and similar scenarios would be less if such negative emissions were to continue beyond the twenty-first century[25–28,29], but further work is required to better quantify this response.

As these processes and uncertainties become better constrained, quantitative relationships may provide a basis for assigning responsibility[30]. They may also be incorporated into long-term planning in the coastal zones subject to inundation, and in those areas where vulnerable populations are likely to relocate[9]. Finally, in conjunction with risks posed by increasing global mean temperature[6], our analysis of SLR will further inform policy for identifying an emissions limit that will prevent or mitigate the dangerous, and essentially permanent, anthropogenic interference with the climate system associated with the irreversible loss of the Greenland and Antarctic ice sheets[7]. ❐

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Additional information

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SUPPLEMENTARY INFORMATION
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Sea-level commitment as a gauge for climate policy

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Supplementary Information

Sea-Level Commitment as a Gauge for Climate Policy

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Model Calibrations of Sea-Level Response

Global Mean Sea-Level Rise (GMSLR) as a continuous function of cumulative emissions was estimated from a series of model simulations. Transient model simulations were started from the year 1750 CE and forced with only historically changing CO_2 concentrations to the year 2000. Models were then forced with CO_2 emissions scenarios that provided cumulative totals of 0, 320, 640, 960, 1280, 2560, 3840 and 5120 Pg of carbon, beyond the year 2000[1]. Published simulations were referenced relative to the baseline year 2000. Here we adjusted all simulations to include GMSRL commitments to climate change between 1750 and 2000 CE and the estimate of historical cumulative emissions (458 PgC). Of the four published models, only UVic 2.8 included all of the emissions scenarios. Simulations using the UVic 2.9, Bern Reduced Complexity and Bern Composite models were performed only with the 0, 1280, 2560, 3840 and 5120 PgC post year 2000 scenarios.

For estimation of uncertainties in the low-emission scenarios, we computed the bias of each model as ratios relative to UVic 2.8 for all scenarios with multi-model ensembles (the higher emissions scenarios), and then emulated the low-emission results relative to the multi-model ensemble mean for all models at the low-emissions scenarios by applying these bias corrections to the relevant UVic 2.8 simulations and the ensemble. With these emulations, all of the calibration emissions levels have four estimated time-dependent sea-level responses. Based on the emulation, model biases are consistent across the full set of runs and are preserved in the four realizations at each emissions level. These four realizations are used to estimate time-dependent ensemble mean and $\pm$1 sigma uncertainties at each emission level, over the interval 1850-11999 AD. Average model biases (e.g., UVic 2.8 Sea-level / Model X Sea-level) are 0.90 (UVic 2.9), 1.17 (Bern Reduced Complexity), and 1.16 (Bern Composite), and the model bias of UVic 2.8 relative to the ensemble mean is 1.04 $\pm$ 0.09.

Interpolation of Model Calibrations

To create functions that simulate ensemble GMSLR as a function of cumulative emissions, we fit third-order polynomials to the mean, $+1\sigma$, and -1σ model estimates, for each time slice illustrated (see Figure 1). For each of these functions, polynomials were calibrated in overlapping ranges of 0-1700 PgC and 1060-5540 PgC, and for plotting purposes were spliced at the 1380 PgC level. These functions define the $\pm1\sigma$ shaded fields (see Figure 1).

Estimation of uncertainties related to scenarios in Table S1 applies these polynomials to their cumulative probability distribution of each emissions pathway. We perform two-dimensional Monte Carlo simulations at each time slice for each scenario. Each simulation assumes Gaussian distributions for both sea level as a function of cumulative emissions, and for cumulative emissions as a function of scenarios, and employs 10,000 simulations in these two dimensions. Reported uncertainties of sea levels in Table S1 thus incorporate both dimensions, so are larger than the uncertainty fields that assume known cumulative emissions (see Figure 1).

<u>Method for having emission scenarios reach zero emissions.</u>

For those scenarios with emissions still above zero at 2100, we used the decline of the RCP2.6 scenario to where it reached zero emissions and scaled it such that the last value of the respective scenario at 2100 declines to zero in the same time that RCP2.6 declines (54 years). All such scenarios are identified with "decline" in their name (or subscript "d" on the Figure 1) and reach zero emissions by 2155 CE.

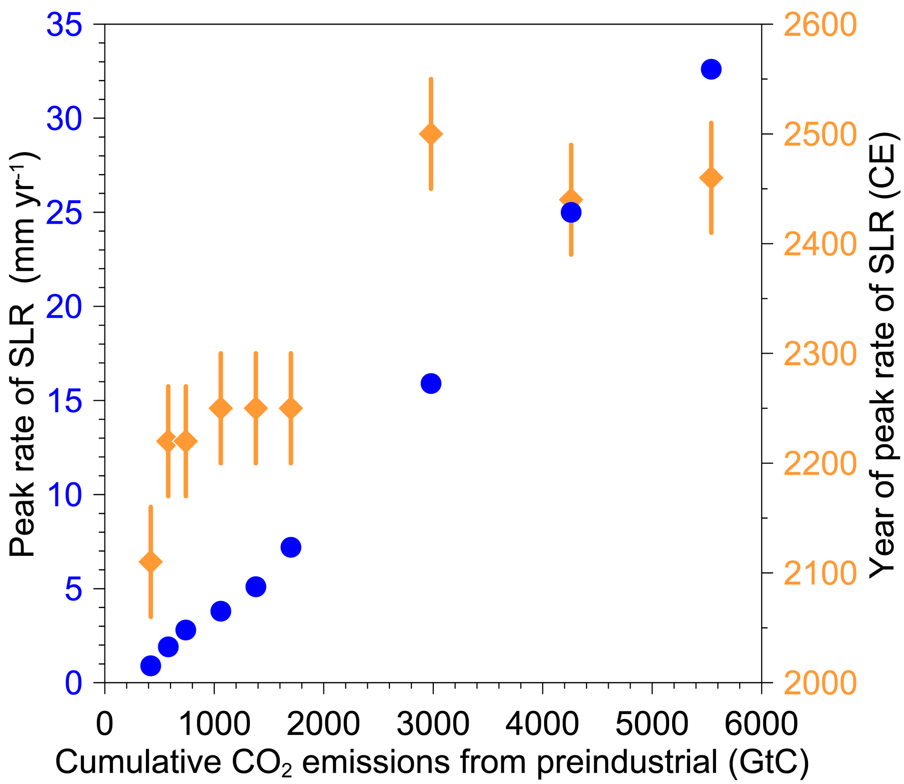

Figure S1. Relation between cumulative emissions from preindustrial and (i) peak rate of sea-level rise (blue symbols) and (ii) year of peak rate of sea-level rise (orange symbols). The vertical orange lines associated with each year of peak sea-level rise represent the 100-year period over which rates of sea level change were averaged.

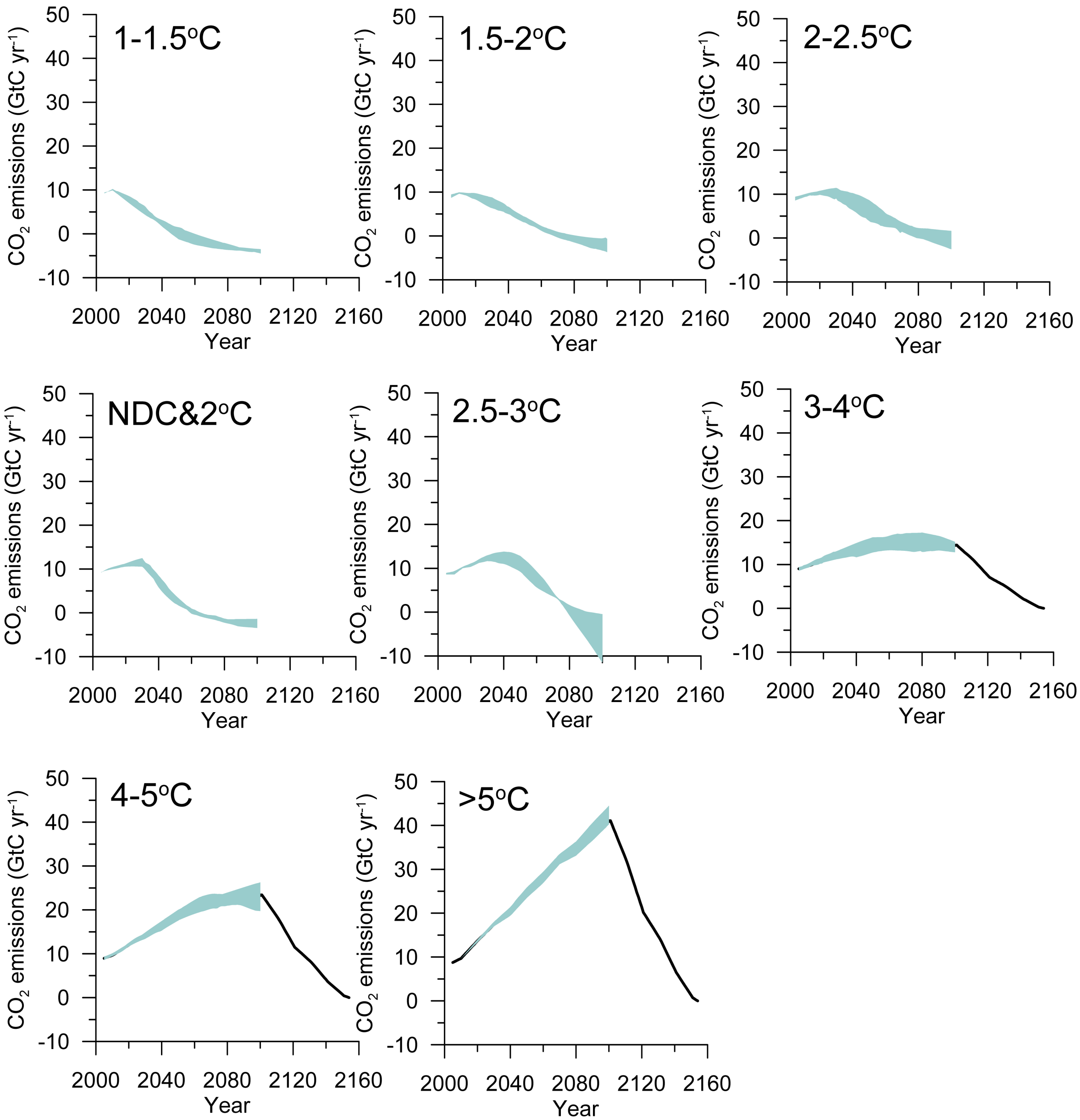

Figure S2. Emission scenarios from Rogelj et al. (ref. 2) that were used to estimate corresponding transient sea-level rise (see Table S1) (emission ranges are 20th-80th percentile). Scenarios were drawn from a wide variety of sources with differing implied end-of-century warming relative to preindustrial, as identified by the names of the scenarios. For those three scenarios with emissions remaining above zero by 2100 CE, we invoke our decline scenario method that is based on the RCP 2.6 scenario and scaled to reach zero emissions within 55 years of the last emission value for each base scenario at 2100 CE (black line extension).

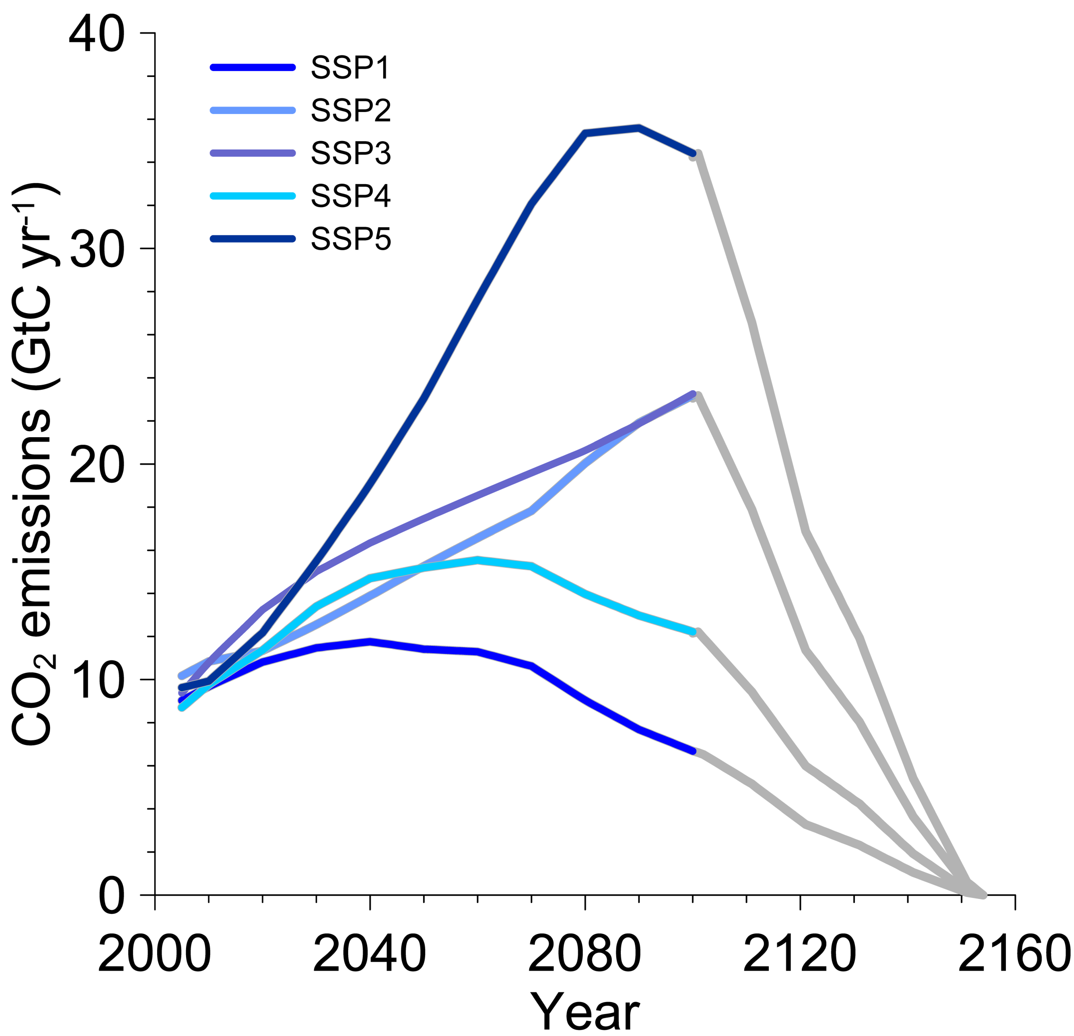

Figure S3. Emission scenarios for the five baseline marker Shared Socioeconomic Pathways (SSPs)[3] that were used to estimate corresponding transient sea-level rise (see Table S1). All five scenarios have emissions remaining above zero by 2100 CE, so we invoke our decline scenario method that is based on the RCP 2.6 scenario and scaled to reach zero emissions within 55 years of the last emission value for each base scenario at 2100 CE (gray line extension).

Table S1. Sea-level rise from total emission scenarios including committed contributions from 1750-2004 emissions.

scenario CO2 emissions (GtC)	cumulative emissions from preindustrial# (GtC)	cumulative emissions 1 σ (GtC)	2300 AD			2500 AD			3000 AD			4000 AD			9000 AD		
			lower range* (m)	sea level* (mean) (m)	upper range* (m)	lower range* (m)	sea level* (mean) (m)	upper range* (m)	lower range* (m)	sea level* (mean) (m)	upper range* (m)	lower range* (m)	sea level* (mean) (m)	upper range* (m)	lower range* (m)	sea level* (mean) (m)	upper range* (m)
1-1.5^{o}C	650	51	0.4	0.6	0.9	0.6	0.9	1.2	1.0	1.4	1.7	1.6	2.0	2.4	2.8	3.7	4.7
1.5-2^{o}C	837	52	0.5	0.8	1.2	0.9	1.2	1.6	1.4	1.9	2.5	2.3	3.0	3.6	5.3	6.8	8.3
NDC <2^{o}C	870	21	0.5	0.9	1.2	0.9	1.3	1.7	1.5	2.0	2.6	2.5	3.2	3.8	6.0	7.4	8.8
NDC 2000 to 2030##	780	20 -10	0.5	0.8	1.1	0.8	1.1	1.5	1.3	1.8	2.2	2.1	2.6	3.1	4.8	5.8	6.9
2-2.5^{o}C	1016	106	0.6	1.0	1.4	1.1	1.6	2.0	1.7	2.6	3.4	3.1	4.2	5.4	7.5	10.3	13.0
2.5-3^{o}C	1128	52	0.8	1.1	1.5	1.2	1.7	2.2	2.2	3.0	3.8	4.0	5.0	6.1	10.0	12.4	14.8
3-4^{o}C	1793	152	1.4	1.8	2.2	2.7	3.2	3.7	5.4	6.5	7.6	10.0	12.1	14.3	20.4	24.6	28.8
3-4^{o}C decline^	2129	152	1.7	2.2	2.6	3.4	4.0	4.6	7.2	8.5	9.7	13.0	15.5	18.0	24.9	29.2	33.5
4-5^{o}C	2214	109	1.8	2.3	2.7	3.7	4.2	4.7	7.8	8.9	10.1	14.1	16.4	18.7	26.0	30.1	34.2
4-5^{o}C decline^	2759	109	2.2	2.8	3.5	4.7	5.5	6.4	10.6	12.1	13.7	18.3	21.3	24.3	31.6	35.7	39.8
>5^{o}C	2889	192	2.3	3.0	3.7	4.9	5.9	6.9	10.9	12.9	14.8	19.0	22.5	26.0	32.5	36.8	41.1
>5^{o}C decline^	3845	192	2.8	4.1	5.3	6.4	8.3	10.2	15.2	18.2	21.3	25.5	30.1	34.6	39.1	42.9	46.7
SSP1 baseline^^ **	1475	0	1.2	1.5	1.8	2.1	2.4	2.8	4.1	4.7	5.3	7.6	8.8	9.9	16.5	19.5	22.5
SSP1 decline***	1631	0	1.3	1.6	1.9	2.5	2.8	3.1	5.0	5.6	6.2	9.1	10.5	11.8	18.9	22.1	25.4
SSP2 baseline	2031	0	1.7	2.1	2.4	3.4	3.8	4.1	7.1	7.9	8.6	12.7	14.6	16.4	24.2	27.9	31.7
SSP2 decline	2571	0	2.1	2.6	3.2	4.5	5.1	5.7	9.8	11.0	12.3	17.2	19.7	22.3	30.0	34.0	38.0
SSP3 baseline	2162	0	1.8	2.2	2.6	3.7	4.1	4.5	7.8	8.6	9.5	13.9	15.9	17.9	25.6	29.5	33.4
SSP3 decline	2703	0	2.2	2.8	3.4	4.7	5.4	6.1	10.4	11.8	13.2	18.1	20.9	23.6	31.3	35.3	39.3
SSP4 baseline	1788	0	1.5	1.8	2.1	2.8	3.2	3.5	5.8	6.5	7.1	10.6	12.1	13.6	21.1	24.6	28.0
SSP4 decline	2073	0	1.7	2.1	2.5	3.5	3.9	4.2	7.3	8.1	8.9	13.1	15.0	16.9	24.7	28.5	32.2
SSP5 baseline	2795	0	2.3	2.9	3.5	4.9	5.7	6.4	10.9	12.4	13.8	18.8	21.7	24.6	32.0	36.0	40.0
SSP5 decline	3596	0	2.7	3.7	4.8	6.2	7.7	9.2	14.4	16.9	19.4	24.2	28.2	32.2	37.8	41.6	45.3

*Global mean sea-leve rise estimates relative to 1750 preindustrial baseline, estimated via Monte Carlo simulations, each with 10,000 realizations of emissions and response to emissions, accounting for uncertainties in both integrated emissions and time-dependent sea level response functions. Monte Carlo simulations are calibrated separately for low-range emissions and high-range emssions to fit the model simulations for each timeslice. The boundary between low-range and high-range calibration was 950GtC for 2300AD, 1250GtC for 2500,3000, and 4000 AD, and 1400 GtC for 9000 AD.

#All emission scenarios except NDC 2000-2030 start at 2005 CE. We added historic emissions from preindustrial to 2004 AD (498 GtC) as derived by the Global Carbon Project (http://www.globalcarbonproject.org/index.htm) to these. See Table S2 for published emissions for 2005-2100.

##For emission scenario NDC 2000 to 2030, no emissions are included beyond 2030 AD. Emissions post 2000 have probabilty percentiles 5th, 25th, 50th, 75th, 95th GtC: 309.2, 312.5, 316.7, 335.8, 340.4.
For purposes of Monte-Carlo modeling this slightly skewed distribution is approximated with Gaussian 324 +/- 14, and pre-2000 historical emissions of 456 GtC are added. See Table S2.

^For extended emissions scenarios 3-4C decline, 4-5C decline, and >5C decline, uncertainties in total emissions are assumed the same as the matching unextended emissions scenarios

^^SSP baseline scenarios are each based on one model with no uncertainty in emissions.

**For baseline SSP1-SSP5 emission scenarios, emission pathways end at above zero at 2100 CE.

***Emission scenarios identified as "decline" are equivalent to same-name emission scenarios except we added an emission pathway to reach zero emissions by 2155 AD. See explanatory text in supplementary materials.

Table S2. Published emission scenarios compared to same scenarios with 1750-2004 emissions added.

scenario	cumulative emissions from 2005 (GtC)*	1 σ	cumulative emissions from preindustrial (GtC)^
1-1.5C	152	51	650
1.5-2C	339	52	837
NDC <2C	372	21	870
NDC 2000 to 2030	324	14	780
2-2.5C	518	106	1016
2.5-3C	630	52	1128
3-4C	1295	152	1793
3-4C decline	1631		2129
4-5C	1716	109	2214
4-5C decline	2261		2759
>5C	2391	192	2889
>5C decline	3347		3845
SSP1 baseline	977		1475
SSP1 decline	1133		1631
SSP2 baseline	1533		2031
SSP2 decline	2073		2571
SSP3 baseline	1664		2162
SSP3 decline	2205		2703
SSP4 baseline	1290		1788
SSP4 decline	1575		2073
SSP5 baseline	2297		2795
SSP5 decline	3098		3596

*All emission scenarios except NDC 2000-2030 start at 2005 CE. We added historic emissions from preindustrial to 2004 CE (498 GtC) as derived by the 2017 Global Carbon Project (http://www.globalcarbonproject.org/index.htm).
^We added historic emissions from preindustrial to 1999 CE (456 GtC) as also derived by the 2017 Global Carbon Project.

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