The transient sensitivity of sea level rise

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Abstract. Recent assessments from the Intergovernmental Panel on Climate Change (IPCC) imply that global mean sea level is unlikely to rise more than about 1.1m within this century, but will increase further beyond 2100. Even within the most intensive future anthropogenic greenhouse gas emission scenarios are higher levels assessed to be unlikely. However, some studies conclude that considerably greater sea level rise could be realized, and a number of experts assign a substantially higher likelihood of such a future. To understand this discrepancy, it would be useful to have scenario independent metrics that can be compared between different approaches. The concept of a transient climate sensitivity has proven to be useful to compare the response of climate models. Here, we introduce a similar metric for sea level science. By analyzing mean rate of change in sea level (not sea level itself), we identify a near linear relationship with global mean surface temperature (and therefore accumulated carbon dioxide emissions) in both model projections, and in observations on a century time scale. This motivates us to define the 'Transient Sea Level Sensitivity' as the increase in the sea level rate associated with a given warming in units of m/century/K. We find that model projections fall below extrapolation based on recent observational records. This comparison suggests that the likely upper level of sea level projections in recent IPCC reports would be too low.

1 Introduction

Our planet is warming as anthropogenic emissions are increasing the atmospheric concentration of carbon dioxide. This warming causes sea levels to rise as oceans expand and ice on land melts. A perturbation in greenhouse gas concentrations changes the balance of energy fluxes between the atmosphere and the ocean surface, and the balance of mass fluxes to and from glaciers and ice sheets. However, the oceans and ice sheets are vast and it takes centuries to heat the oceans, and millenia for ice sheets to respond and retreat to a new equilibrium (Clark et al. 2018; Li et al., 2013; De Conto and Pollard, 2016; Oppenheimer et al. 2019; Clark et al., 2018). In this sense the ice sheets and oceans have a large inertia: An increase in forcing result in a long-term commitment to sea level rise. Simulations by Clark et al. (2018) indicate an equilibrium sea level sensitivity of ~2m/100 GtC emitted CO_2. The equilibrium sensitivity can be compared to paleo-data (e.g. Foster and Rohling, 2013). Initially the response to a perturbation in forcing is a flux imbalance, i.e. a change in the rate of sea level rise. Hence, sea level rise by 2100 does not immediately reflect the temperature in 2100, instead the entire pathway since the forcing change was introduced is important. We therefore expect 21st century sea level rise to better correlate with the century averaged temperature than temperature itself by 2100. Following this, we here propose to linearize the relationship between average rate of sea level rise and temperature increase representing the entire preceding century. The slope of this relationship shows how sensitive sea level is to century time-scale warming, and is referred to as transient sea level sensitivity (TSLS). The intercept - where the sea level rate is zero - we interpret as a *balance temperature*. The relationship between the temperature and the rate of sea level rise has previously been noted (e.g. Warrick and Oerlemans, 1990), and has been used to motivate semi-empirical models of sea level rise (Rahmstorf, 2007; Grinsted et al. 2010; Church et al. 2013; Kopp et al., 2016; Mengel et al., 2016). A key assumption behind such semi-empirical model projections is that the sensitivity implied by historical records is stationary and hence can be extrapolated into the future. However, there may be processes that can cause future sensitivity to be different from the past (Church et al., 2013). These changes can broadly be categorized as being due to a non-linear response to forcing, or due to a non-stationary response where the response depends on state of the system. E.g. the sensitivity of small glaciers to warming will depend on how much glacier mass there is left to be lost, and we therefore expect this to have a non-stationary response. Nature is complex and will be both non-linear and non-stationary, and this places limits on extrapolation. Regardless, the sea level response can always be characterized using the TSLS metric, and we can compare and contrast different estimates.

2 Data

Here we restrict our analysis to published estimates of the Global Mean Sea Level (GMSL) rate. We use three estimates of the historical rate: 1) the tide gauge record (TG) for the period 1900-1990 (Dangendorf et al., 2017); 2) the satellite-altimetry record (Sat; Ablain et al., 2019) from 1993-2017; 3) a reconstruction for the 1850-1900 pre-industrial period (PI; Kopp et al., 2016). The corresponding temporally averaged temperature anomalies and uncertainties are calculated from the HADCRUT4 observationally based ensemble of Global Mean Surface Temperature (GMST) reconstructions (Morice et al., 2012). We follow IPCC's fifth assessment report (AR5; Church et al., 2013) and use a 1986-2005 baseline for temperature anomalies to avoid introducing additional uncertainties from in re-baselining the IPCC assessed projections. The historical estimates are compared to the projected sea level rate and temperature from 2000-2100 from two recent IPCC reports for a range of scenarios: the AR5 (Church et al., 2013), and the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; Oppenheimer et al., 2019). Finally, we show the results of an expert elicitation (Bamber et al., 2019) which pertain to scenarios with 2°C and a 5°C warming by 2100 relative to the pre-industrial. These estimates are shown in Figure 1.

3 Methods

The relationship between temperature and GMSL rate is estimated for each group of points using linear regression. The observational estimates of both temperature and sea level rate (Figure 1, black) are uncertain. We use Monte Carlo sampling to propagate these uncertainties to our estimates of the line parameters listed in Table 1. Uncertainties in the projections assessed in AR5 and SROCC are specified as a central estimate and a likely range for both temperature and sea level (Church et al., 2013; Oppenheimer et al. 2019; Mastrandea et al., 2010). The IPCC sources do not provide information on the uncertainty covariance between projections of temperature and sea level. However, we observe that the upper and lower likely limits of temperature paired with the corresponding limit of sea level falls very close to the curve between central estimates (see Figure 1). This indicates that there is a very high degree of covariance. For simplicity, we therefore assume full covariance between uncertainties in projected temperature and projected sea level, and depict this using the slanted error bars displayed in Figure 1.

Table 1 reports several estimates of TSLS, and we want to understand if each is substantially different to the corresponding observational estimate considering the uncertainties. We therefore test if the absolute difference is larger than zero considering uncertainties in both estimates, using a standard two-tailed hypothesis test assuming normality.

We show the total cumulated anthropogenic CO_2 emissions associated with a given temperature as a secondary horizontal axis in Figure 1 (IPCC, 2013; Meinshausen et al., 2011). We established this relationship using both historical data, and the mid-range temperature projections for the RCP scenarios, and thus does not account for uncertainties in the e.g. climate sensitivity. The cumulated emission and temperatures were averaged over the same time intervals.

4 Results

The estimates of the temporal average rate of sea level rise against corresponding temporal average of GMST from a variety of sources are shown in Figure 1. The AR5 and SROCC projected rate of sea level rise over the 21st century from different scenarios show a close correspondence with projected temperatures (Figure 1, red and blue). We fit straight lines to these projections, and the slope gives a TSLS of $0.27^{+0.03}_{-0.01}$ m/century/K for AR5, and $0.39^{+0.04}_{-0.03}$ m/century/K for the models assessed in SROCC (Table 1). The historical rate of sea level rise in three different periods also show a close relationship to warming (Figure 1, black). From this we estimate a TSLS of 0.40±0.05 m/century/K. Finally, we represent the results of expert elicitation of 21st century sea level rise under two different warming scenarios (Bamber et al. 2019), which yield a sensitivity of $0.42^{+0.31}_{-0.09}$ m/century/K. The balance temperatures corresponding to all TSLS estimates are listed in Table 1.

5 Discussion

We find that both model projections and observations show a near linear relationship between century averaged temperature change and the average rate of sea level rise (Figure 1). A linearization captures the bulk of the sea level response on these time scales. This shows that the concept is sound and that TSLS is a suitable new metric for assessing the graveness of global mean sea level changes.

The relationship deduced from model projections differs systematically from extrapolation of the observational relationship (Table 1 and Figure 1). Sea level projections assessed in AR5 have a substantially smaller TSLS than exhibited by historical observations, whereas SROCC is more comparable (Table 1). The greater SROCC sensitivity is driven by the warmest scenario and the higher TSLS is accompanied by a warmer balance temperature that is far from the observationally based estimate (Table 1). Future TSLS may well be different from the past due to non-linearities or non-stationarities in the relationship (Church et al., 2013). Thus, the discrepancy highlighted by Figure 1 does not necessarily demonstrate a bias in model projections, but as a minimum call for a yet to be prepared detailed explanation. Ideally, we would test the models using hind casts to verify their ability to reproduce the past. Unfortunately, such hind-casts are unavailable for sea level projection models assessed in both AR5 and SROCC. This is critical as Slangen et al. (2017) identified substantial biases in hind-casts of Greenland surface mass balance, glacier mass loss, and deep ocean heating. These biases increase the modelled sea level rise over the 20th century by ~50%. The discrepancy between historical and projected sensitivities is puzzling considering the lack of possibilities for a validation of the model projections.

In order for non-linearities to explain the discrepancy between the past and future relationship between warming and sea level rate, it is evident from Figure 1 that these would have to be sub-linear. This is incompatible with our current understanding. Major non-linearities are not expected this century according to the process knowledge encoded in the model projections assessed in both AR5 and SROCC, with SROCC presenting some signs of a super linear response (Figure 1). Antarctica, in particular, may have a super-linear response (Oppenheimer et al. 2019; DeConto and Pollard, 2016; Edwards et al. 2019; Bamber et al. 2019). Further, expert elicitation results overlap with the relationship found for the historical period but with a higher sensitivity (Table 1), which may be due to an anticipated super-linear response not captured by AR5 and SROCC assessment of model results. Antarctic rapid ice dynamics was considered as scenario independent in the IPCC fifth assessment report (AR5; Church et al., 2013), in stark contrast to later results (Oppenheimer et al. 2019; DeConto and Pollard, 2016; Edwards et al. 2019). We therefore propose AR5 to have a TSLS likely upper bound, which is biased low.

6 Conclusion

We define a new Transient Sea Level Sensitivity (TSLS) metric, which relates the rate of global mean sea level rise to global mean surface temperature. We find that this metric can account for most of sea level response to temperature increase on a hundred-year time scale. The TSLS metric is useful as it allows for model sensitivity comparisons, even if the models have not been run for the same set of scenarios. By framing the transient sensitivity in terms of temperature we separate the sea level sensitivity from climate sensitivity to a large extent. This allows for easier comparison between sea level models that are forced by different Earth system models.

We compare the model projections over the 21st century assessed by the IPCC with historical records from 1850-2017. We find that the model projections assessed in both AR5 and SROCC fall substantially below an extrapolation of historical records (Figure 1). This is reflected in the estimates of TSLS and balance temperature, which does not match the historical estimate (Table 1). Future sensitivity may be different from the past as the relationship between warming and sea level rate may be non-linear or non-stationary. We reason that a non-linearity cannot explain the mismatch as the required curvature would be inconsistent with process knowledge encoded by model projections assessed in SROCC and expert expectations (Oppenheimer et al. 2019; Bamber et al., 2019). Based on our analyses we cannot fully reject that the sensitivity has changed between the historical period (1850-2017) and the projection period (2000-2100). The major sea level contributors have characteristic response times of several centuries (Clark et al. 2018; Li et al., 2013; DeConto and Pollard, 2016; Oppenheimer et al. 2019; Church et al. 2013), which suggests that the sensitivity is unlikely to change substantially between these periods. The outcome of an expert elicitation is more consistent with an extrapolation of the historical relationship than AR5 and SROCC (Figure 1 and Table 1). Further, Slangen et al. (2017) identified substantial biases in process model hind-casts, which draws into question whether the AR5 and SROCC assessed models would be able to reproduce historical sea level rise. This is supported by our interpretation of the TSLS discrepancy between past and future. Our analysis implies that the model states used for the assessment in SROCC are too close to balance for present-day conditions and at the same time underestimate TSLS. Taken together this suggests that the projected global sea level rise by the end of this century in various IPCC reports are at best conservative and consequently underestimate the upper bound of likely sea level rise by the end of this century.

Data availability

All data has previously been published and are publicly available.

Author contributions

AG designed the research study and conducted the analysis. AG and JHC interpreted the results and wrote the manuscript.

Competing interest

The authors declare that they have no conflict of interest.

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Table 1: Transient sea level sensitivity, and balance temperatures estimated from different sources. Intervals are likely ranges (17-83%). Symbols indicate that the difference from the observational estimate is significant at p<0.05 (*), and p<0.1 (†) using a two-tailed test assuming normality.

	Sea level sensitivity m/century/K	**Balance Temperature °C**
Observations	0.40 [0.35 – 0.44]	-0.70 [-0.77 – -0.64]
SROCC	0.39 [0.36 – 0.43]	-0.14† [-0.42 – 0.23]
AR5	0.27* [0.26 – 0.30]	-0.63 [-0.70 – -0.41]
Expert elicitation	0.47 [0.33 – 0.85]	-0.37* [-0.36 – -0.05]

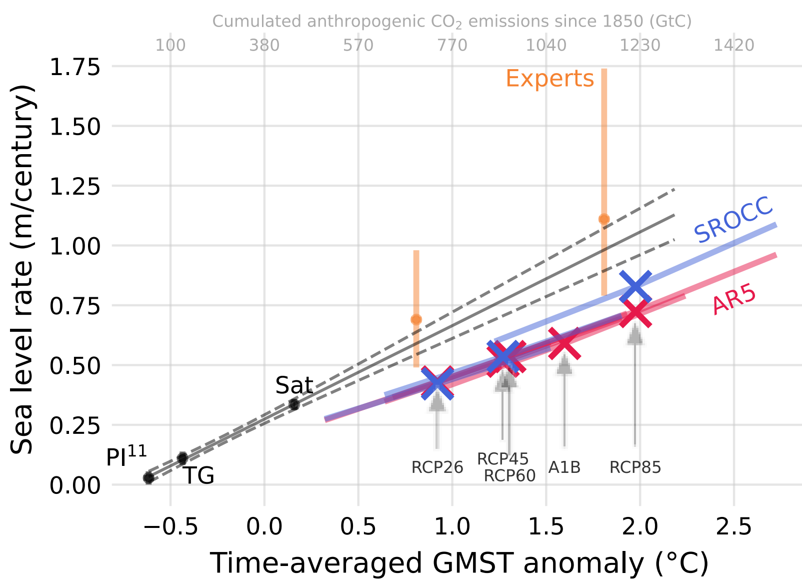

Figure 1: The rate of sea level rise versus long term average temperature as seen in observations (black), in model projections (red/blue), and expectations in an expert elicitation (orange). Each point represents an average over a time period (PI: 1850-1900; TG: 1900-1990; SAT: 1993-2017; AR5/SROCC/Experts: 2000-2100). Sea level projections as assessed in AR5 and SROCC systematically fall below what would be expected from extrapolating observations to warmer conditions, as well as below the expert elicitation. Error bars show estimated likely ranges (17-83%). Likely ranges for SROCC and AR5 are shown as slanted error bars.