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The transient sensitivity of sea level rise

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Abstract. Recent assessments from the Intergovernmental Panel on Climate Change implies that global mean sea level is unlikely to rise more than about 1.1m within this century, but with further increase beyond 2100, even within the most intensive future anthropogenic carbon dioxide emission scenarios. However, some studies conclude that considerably greater sea level rise could be realized, and 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 response 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 indicates 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 change the balance of energy fluxes between the atmosphere and the ocean surface, and in the 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 (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 CO2. 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. 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 construct semi-empirical models of sea level rise (Rahmstorf, 2007; Grinsted et al. 2010; Church et al. 2013; Kopp et al., 2106; Mengel et al., 2016). Hence, sea level rise by 2100 does not immediately reflect the temperature in 2100, instead the entire pathway since the forcing change

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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 consider the relationship between average rate of sea level rise and temperature increase representing the entire preceding century (Figure 1). The slope of this relationship shows how sensitive sea level deduced from observations or models 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 - is interpreted as a balance temperature.

2 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). 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. Observation based data indicate a TSLS of 0.39±0.05 m/century/K with a balance temperature of -0.71±0.08 °C (see Table 1 and Data & Methods). Future TSLS may well be different from the past, as the sea level response is not necessarily completely linear in warming (Church et al. 2013). 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). Expert elicitation results overlap with the relationship found for the historical period but with a higher sensitivity ($0.42^{+0.31}_{-0.09}$ m/century/K), which may be due to an anticipated super-linear response. It is therefore disconcerting that the relationship deduced from model projections are systematically below observational constraints (table 1 and figure 1). This does not automatically demonstrate a bias in model projections, but as a minimum call for a detailed explanation. 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 which is biased low. The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; Oppenheimer et al., 2019) has a larger TSLS of 0.39±0.04 m/century/K in better agreement with the observations but has a balance temperature far from that of the observations (table 1). Our analysis therefore 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 likely sea level rise by the end of this century.

Data & Methods

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 AR5 (Church et al., 2013) and use a 1986-2005 baseline for temperature anomalies, and define 1850-1900 as the pre-industrial (PI).

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Uncertainties in AR5 and SROCC projections are given 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). We simply assume full covariance between uncertainties in projected temperature and projected sea level, and depict this using slanted error bars in figure 1. The uncertainties fall very close to the line connecting central estimates, supporting this assumption. We use three estimates of historical global mean sea level change rates based on: 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 1993-2018; 3) a reconstruction for the pre-industrial period (PI; Kopp et al., 2016). 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. We show the 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.

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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 (†).

	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]

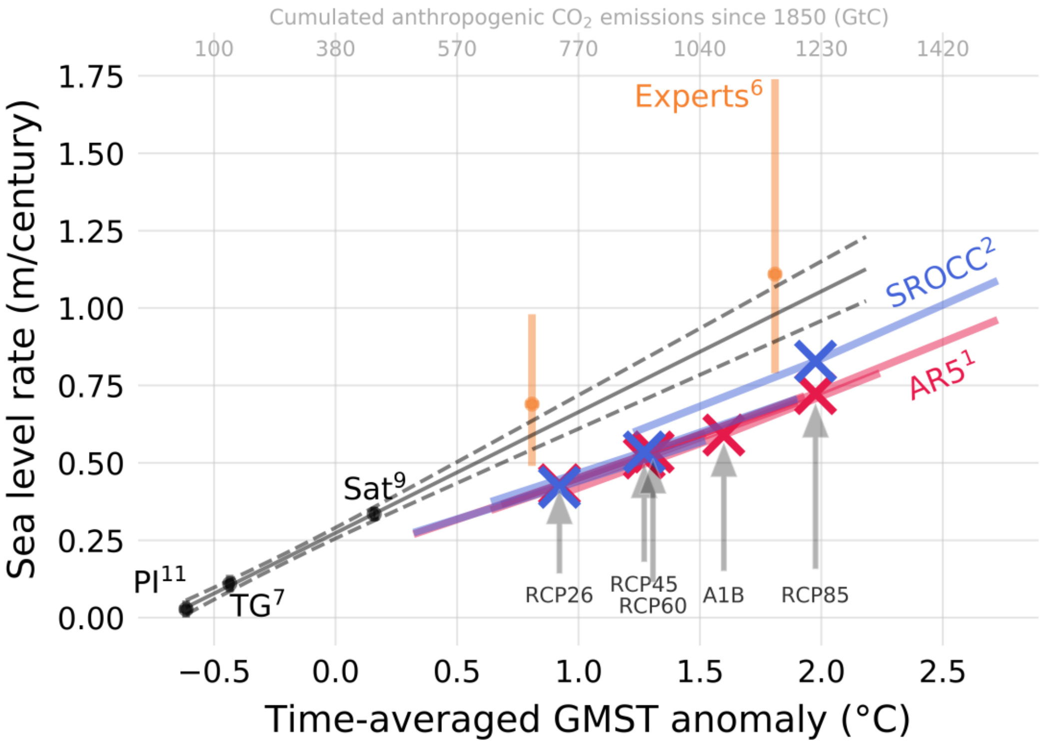

Figure 1: The rate of sea level rise versus long term average temperature as seen in observations (black), in model projections (red/blue), and expectations in an expert elicitation (orange). Likely ranges for SROCC and AR5 are shown as slanted error bars. Sea level projections as assessed in AR5 and SROCC systematically fall below what would be expected from extrapolating the observations to warmer conditions as well as to the expert elicitations. Error bars show the estimated likely ranges (17-83%).