Response to Reviewer #2

> *I thank the authors for considering my comments on the initial submission. I think that manuscript has been improved, but I still have some concerns, as I explained below. Some of them might be a matter of style, and thus are debatable, but the authors and the editor may want to think about them once more.*

> *Improvements: The main message of the manuscript is now clearer. The study defines a transient sensitivity and attempts to estimate from observations and from model runs. These estimation shows a discrepancy, and the authors conclude that the models may be underestimating future sea-level rise.*

We agree that the manuscript has improved a lot based on your feedback. Thank you. We hope we have improved it further this time around and made the conclusion(s) even more clear.

> *1) One main concern is again related to the length of the manuscript, whereas at the same time it compresses important information too strongly. I do not really understand why the authors want to cram all that information, as the length of the manuscript is by far not close to usual limits.*

We agree that we are not pressed for space. We will see what we can add to accommodate your concerns. Therefore, we have expanded the manuscript considerably and now include a section that articulates some of the potential caveats related to non-linearity and non-stationarity that were raised in the discussion of the manuscript

> *For instance, the the main point of the study is the disagreement between the estimations of the transient sensitivity from observations and models. The reader would think that the methodology, including a clear description of the uncertainties, biases, etc. is crucial. Yet, the method section devotes just one sentence to describe the estimation of uncertainties (We use Monte Carlo sampling...)- Well, Mane Carlo sampling can be accomplished in many different ways, for instance to preserve autocorrelation of the regression residuals, with replacement or without replacement. The reader does not even know how many samples enter the regression - it seems that just 3 data points (?). If this is true, how is Monte Carlo re sampling really accomplished ?*

It appears to us that this is the primary concern: That the referee would like a more expanded description of the methods section in particular.

It really is very simple what we are doing in this Monte Carlo sampling, hence the brief explanation. The number of observational/historical points is 3, as should be clear from the data section, and figure 2. But we have no space concerns and so you are correct, it would be good to state it in the methods section too. The three estimates come from different studies, and are well separated in time and it is therefore reasonable to assume the uncertainties are independent which makes the MC sampling trivial. We have added more detail to make this clear. We have revised the description in the methods text accordingly:

"The relationship between temperature and GMSL rate is estimated for each group of points using linear regression. The three observational estimates of both temperature and sea level rate

(Figure 2, black) are uncertain. We take the uncertainties to be independent as the three estimates are sourced from separate studies using different data sources, different methods, and are well separated in time. We assume independent gaussian errors which we propagate to our estimates of the line parameters listed in Table 1 using Monte Carlo sampling."

Just to be 100% clear in this reply then here's a verbose description and a code block (Python) that you can compare to the above description. We have three x-y pairs, each with their own σ_x and σ_y errors. We treat these errors as independent and gaussian. The source for the σ_y-values are the same three publications that provide the y-values (I.e. the sea level rate estimates). The σ_x errors are obtained from the HadCRUT4 ensemble as described in the data section.

```
Nmc = 10000
slopes = np.full((Nmc),np.nan)
T0s = np.full((Nmc),np.nan)
o_intercept = np.full((Nmc),np.nan)
for ii in range(Nmc):
    p = np.polyfit(x+np.random.randn(x.size)*sigmax,
                   y+np.random.randn(y.size)*sigmay,1)
    slopes[ii] = p[0]
    o_intercept[ii] = p[1]
    T0s[ii] = -p[1] / p[0]
```

Note that we have compared the above MC derived uncertainties to traditional weighted least squares regression (using statsmodels.regression.linear_model.WLS). The results are virtually identical. Also note: WLS also assume gaussian independent errors, but only allows for errors in the y-direction.

> *2) Perhaps my most important concerns is indeed related to that very limited number of samples. The study claims that although the physical processes relating global mean temperature and sea level rise would in principle render that link non-linear,, the data indicate that the link is close to linear., at least in the range of the observed changes. I struggle to understand this claim when the available number of samples is just 3. …*

First: We do <u>not</u> just use the three historical points as an argument for linearity. So, the criticism here seems somewhat misplaced. We observe that <u>the models</u> (AR5 and SROCC) show a near-linear behavior. That is not just three points. In the case of AR5 we have a near perfect linear relationship for 15 pairs of values (including the upper and lower ranges), and similar for the 9 SROCC points. We then also find that the observations are close to linear. That may not be very impressive given that N=3, but this observation does not stand alone. Thus, we have three separate groups of points, and all of them are near linear. For all groups of points the linear correlation coefficients are greater than 0.98 (see table R1). Because of this we think we are justified in saying: "*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 2)*".

The relationship between the SL rate and temperature may not be completely linear. We agree, and we explicitly state this in the manuscript already. However, we presume that we can agree that the rate is highly correlated with temperature. The relationship might not be linear, but if it is reasonably close to monotonic, then it makes sense to make a first order linear approximation over a given range. And this is precisely what we are doing. We do not argue that the relationship is linear. Indeed, we very explicitly note that it could very well be non-linear and that there are limits to an extrapolation. But within those limits the linearization we perform makes sense.

Table R1: Linear Pearson correlation coefficients of all the points in the historical, AR5 and SROCC. For the AR5/SROCC values two separate correlations are calculated either including or excluding the upper and lower likely limits. Correlation and p-values were calculated using scipy.stats.pearsonr.

	N	Pearson Corr	p-value
Historical observations	3	0.9993	0.023
AR5 (incl. upper/lower)	15	0.997	$4*10^{-16}$
AR5 (only central estimates)	5	0.994	0.0006
SROCC (incl. upper/lower)	9	0.982	$2*10^{-6}$
SROCC (only central estimates)	3	0.998	0.034

We have added some correlations to the results section and explicitly state N.

> *... Even when looking at Fig 1, I would even go so far to say that a regression line drawn using the first two observational data points, PI and TG would not hit the third data point Sat even considering the uncertainty ranges.*

We perform this test in Figure R2. It turns out that the Sat estimate *is* consistent with the extrapolation of a line based on PI and TG alone.

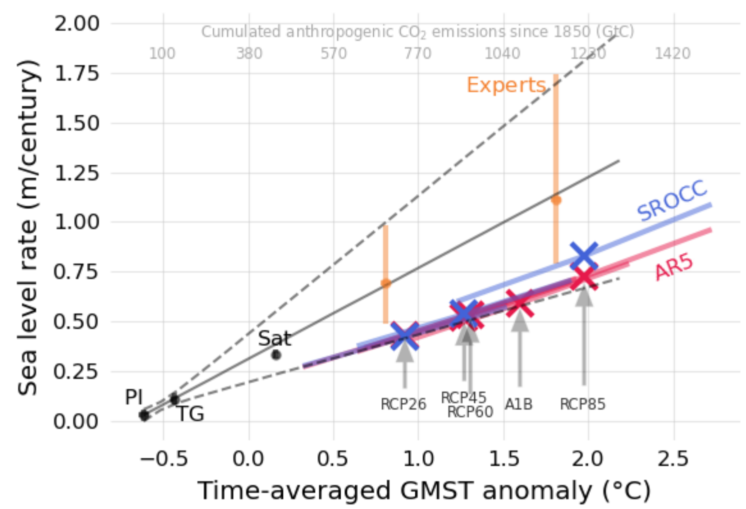

Figure R2: A version of figure 2 where the satellite altimetry data has been excluded from the observational regression (black line). The uncertainties in the regression become much greater. Note how the extrapolation based on TG and PI alone is consistent with the satellite altimetry estimate.

> *I wonder if the claim of linearity would hold in the perfect world of climate models. For instance, if we also include the corresponding pre-industrial and 20th century data points derived from one one model run, would we see a linear relationship through the whole period from pre-industrial to 2100 ? If the linear assumption of this study holds, this should be the case. Actually it should be the case for all individual model runs, as each run would be a surrogate for observations. If this assumption does not hold for the individual model runs - for instance if the*

> *the scenario data points fall bellow or above the regression line drawn with the PI and 20th century data points, then the linear hypothesis would not be correct, and the comparison shown in Figure 1 would not be indicative of an under or overestimation by the models.*

We also wonder what models would say for the past. At the moment it is impossible to do anything but speculate, because unfortunately there are no hindcasts with the same models used for projections and we very much encourage such studies. Here's how we frame this in the manuscript:

"Ideally, we would test the models using hindcasts to verify their ability to reproduce the past. Unfortunately, such hindcasts 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 hindcasts of Greenland surface mass balance, glacier mass loss, and deep ocean heating. Adjusting for these systematic biases increase the modelled sea level rise over the 20th century by ~50%."

Note that we restrict our claim of linearity to exactly what we observe. We observe a linearity for the 21stC model response. We do not claim nor do we want to that this is universal and necessarily leave open whether the same linearity could hold for the past. We explicitly discuss how the relationship can be broken by non-linearities and non-stationarities.

We have added a new section called "reflections on the method". In this new section we discuss how comparisons between past and future TSLS, vs hindcasts and propose using past TSLS as an emergent constraint. We write:

"*Sea level projections in the IPCC Fifth Assessment Report (AR5; Church et al., 2013), and the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; Oppenheimer et al., 2019) are unfortunately not accompanied by hindcasts using the same model framework used for projections. It is therefore impossible to verify that these models can reproduce historical sea level rise. We can, however, compare the TSLS of model projections to the TSLS implied by historical records, and this can serve as a reality check. We have to keep in mind that TSLS potentially can change over time, and that a comparison between different periods cannot be as conclusive. We therefore appeal that future sea level based on modelling are not only used for projections but also include results based on model hindcasts. Ice sheets and ocean heat content has multi century response times and this can lead to model drift if the model is not perfectly initialized. To inform about the future, it is therefore a necessity but not sufficient that model can reproduce the total sea level rise over the 20th century. It is critical that sea level models also have sensitivities that are compatible with observations. We therefore propose that the historical TSLS should be used as an emergent constraint of sea level models."*

> *This would be one possibility., perhaps there are others. What I mean here is that the manuscript leaves open some avenues to support or reject the main linear hypothesis, and I do not see why they are not pursued further in this study.*

Looking into hindcasts is impossible because these model hindcasts do not exist. So unfortunately, we will have to leave some questions open. We now draw attention to these open questions and the importance of hindcasts in the both the conclusion and the new "reflections on the method section".

Further we would argue that it is incorrect to consider the linear approximation a hypothesis, and an approximation is not a hypothesis that can be rejected. The linear approximation is supported by the very high Pearson correlation coefficients (See table R1).

> *3) The linear hypothesis raises some additional points. …*
>
> *… The authors agree that the two main process causing sea level rise (thermal expansion and land ice melting) have a vastly different temperature sensitivities. Then the question arises as to why the linear link between temperature and sea level rise would hold. Is it because the sea level rise is still too small to show that non-linearly ? is it because of these two processes only one has been dominant so far ? There are estimations of the contribution of these processes to 20th century sea level rise. Frederike et al 2020, (doi: /10.1038/s41586-020-2591-3) found that the main mechanisms during the 20th century was land-ice melting and that that contribution has grown larger through time. . It is plausible to assume that for the preindustrial period the main mechanism was water expansion. Thus, why is the link still linear?*
>
> *I am of course aware that these questions are not easily to solve, but why not include here a a first step ?*

First, we want to stress that we do not have a linear hypothesis as already alluded to above. We have a linear first order approximation. This is an important distinction, and in our opinion, this also reduces the burden of proof drastically. We believe that our manuscript already makes this very clear. E.g. "*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.* "

We acknowledge the shifting balance of the budget as nicely demonstrated by Frederikse et al. 2020. We also acknowledge that the different contributors have different sensitivities. However, it is simply wrong to conclude that this must give rise to a non-linearity. Consider the illustrative example in figure R2. Here, we have two contributors, both modelled as being completely linear in temperature, yet in relative terms the sea level budget starts out being dominated by expansion, but eventually ice melt takes over.

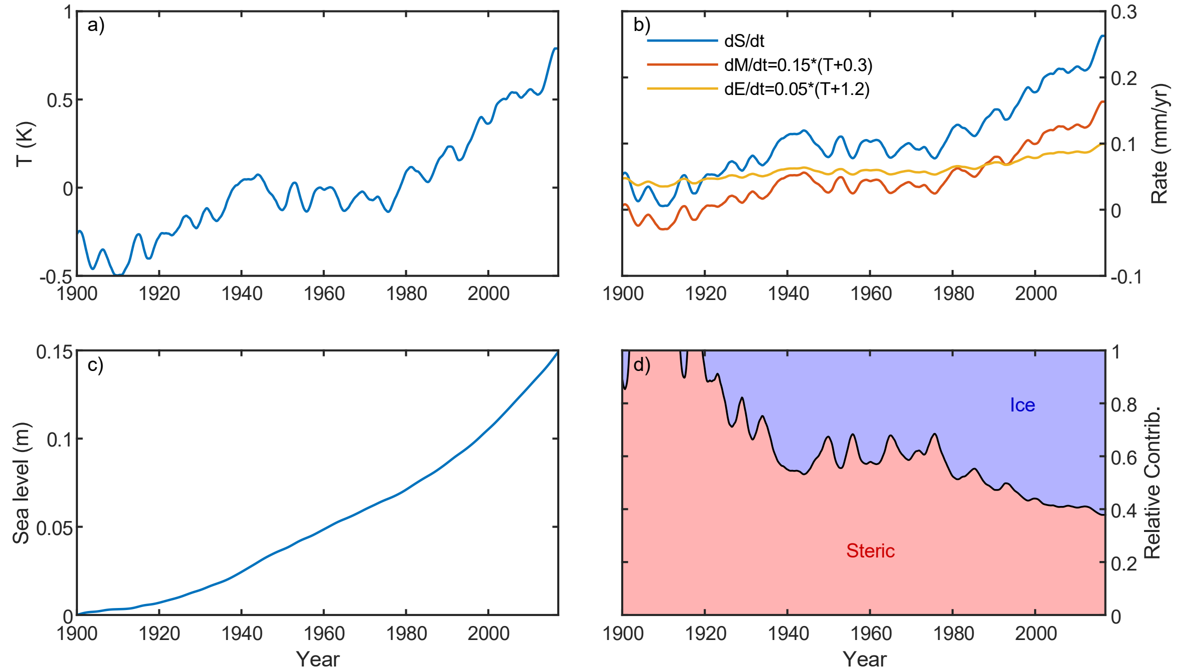

Figure R2: Illustrative example demonstrating how changing relative sea level contributions can arise in a world where all contributors respond linearly to temperature. a) temperature forcing; b) The rate of sea level rise ($\dot{\boldsymbol{S}}$) is modelled as the sum of two contributors: ice melt ($\dot{\boldsymbol{M}}$) and steric expansion ($\dot{\boldsymbol{E}}$); both contributions are modelled as linear in T. c) The sea level curve obtained by integrating $\dot{\boldsymbol{S}}$. d) The relative contributions from Ice Melt and Steric expansion (e.g. $\dot{\boldsymbol{E}}/\dot{\boldsymbol{S}}$).

To conclude, the referee presents an intuitive argument for why one might think that it must be non-linear and changing over time. However, in this case intuition turns out to be insufficient, and leads one to the wrong conclusion. Figure R2 demonstrate that you can easily have changing relative proportions in a linear world. We believe this to be a common misunderstanding, and so we have added this illustrative example and an explanation of it in a new section called "reflections on the method".

> *In summary, essentially the very short manuscript is based just in a few regressions - with s very small sample size. The process leading to those results is not clearly explained and the consequences of those results are not really explored.*

We have expanded the manuscript, and we hope that the methods are sufficiently clear now.

The main contribution is the idea and the concept of TSLS rather than the results of the regressions. The idea is motivated by the physical reasoning that the initial response to a change in forcing is change in the balance of fluxes to the ocean heat reservoir and the land ice reservoir. That said the regressions are all based on data with extremely high correlations (See table R1). The linearization (=linear approximation) is thus clearly justified by both models and data.

We explore the consequences of the idea by comparing the TSLS implied by the different regressions. In those comparisons we find that model sensitivity for the 21st century falls below the sensitivity in historical data. It would of course be better if we could calculate the model sensitivity over the exact same period we have observations. Unfortunately, this is impossible as the required hindcasts do not exist. So, we are in a situation where no proper historical validation is currently possible. The past vs future TSLS comparison we perform may not be as conclusive, but it is the next best thing. There are of course caveats in this past/future comparison. We spend a lot of text discussing the caveats and TSLS can change over time.

In the new revision we propose that next gen sea level models should include hindcasts and further argue that TSLS can serve as a valuable emergent constraint of sea level models.

The transient sensitivity of sea level rise

Aslak Grinsted[1] and Jens Hesselbjerg Christensen[1,2]

[1]Physics of Ice, Climate and Earth, Niels Bohr Institute, University of Copenhagen, Denmark.
[2]NORCE Climate, Bergen, Norway

Correspondence to: Aslak Grinsted (aslak@nbi.ku.dk)

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 global mean temperature response of climate models to specific radiative forcing scenarios. Here, we introduce a similar metric for sea level ~~science~~response. 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~~ future projections estimated on climate model responses ~~-~~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~~ therefore 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~~ then expresses how sensitive sea level is to century time-scale warming, and ~~is~~ we will refer ~~red~~ to it as the *transient sea level sensitivity* (TSLS). The intercept - where the sea level rate of change 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 the 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 Reflections on the method

Sea level projections in the IPCC Fifth Assessment Report (AR5; Church et al., 2013), and the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; Oppenheimer et al., 2019) are unfortunately not accompanied by hindcasts using the same model framework used for projections. It is therefore impossible to verify that these models can reproduce historical sea level rise. We can, however, compare the TSLS of model projections to the TSLS implied by historical records, and this can serve as a reality check. We have to keep in mind that TSLS potentially can change over time, and that a comparison between different periods cannot be as conclusive. We therefore appeal that future sea level based on modellings are not only used for projections but also include results based on model hindcasts. Ice sheets and ocean heat content has multi century response times and this can lead to model drift if the model is not perfectly initialized. To inform about the future, i~~I~~t is therefore a necessity but not sufficient that models ~~are able to~~can reproduce the total sea level rise over the 20th century. It is critical that sea level models also have sensitivities that are compatible with observations. We therefore propose that the historical TSLS should be used as an emergent constraint of sea level models.

Frederikse et al. (2020) find multi-decadal variability in the relative contributions of the major sea level contributors over the 20th century. In recent years the contribution from ice melt has increased relative to that from thermal expansion. We also expect the individual major sea level contributors to have different sensitivities to warming. One might be misled to conclude that TSLS must be changing substantially already. Here, we demonstrate that even in a completely linear world we would expect to have the budget to be changing over time (see Figure 1). For illustrative purposes we construct a simple linear model where global sea level rise ($\dot{S}$) only has two contributors: ice mass loss ($\dot{M}$) and thermal expansion ($\dot{E}$). We write:

$$\dot{S} = \dot{M} + \dot{E}.$$

These two contributions each respond linearly to warming.

$$\dot{M} = a_M T + b_M$$

$$\dot{E} = a_E T + b_E$$

We insert and get a linear model for the sea level rate:

$$\dot{S} = (a_M + a_E)T + b_M + b_E$$

The proportion of sea level rise due to ice melt becomes

$$\frac{\dot{M}}{\dot{S}} = \frac{a_M T + b_M}{(a_M + a_E)T + b_M + b_E}.$$

This is not generally constant in T (see F~~f~~igure 1), demonstrating that a changing proportion of ice melt does not necessarily imply a changing sensitivity to warming. Church et al. (2013) note that it is very likely that ice-sheet dynamical changes have contributed only a small part of the historical sea level rise, implying that semi-empiric models are unlikely to be able predict a large future contribution. The fact that ice dynamical changes have only been a minor contributor historically, while we expect it to play an increasingly important role in the future ~~(Church et al., 2013)~~ does not imply that TSLS cannot be close to stationary.

3~~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)~~ AR5 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 (~~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 2~~1~~.

4~~3~~ Methods

The relationship between temperature and GMSL rate is estimated for each group of points using linear regression. The three observational estimates ~~-~~of both temperature and sea level rate (Figure 2~~1~~, black) are uncertain. We take the uncertainties to be independent as the three estimates are sourced from separate studies using different data sources, different methods, and are well separated in time. We assume independent gaussian errors which we propagate to our estimates of the line parameters listed in Table 1 using ~~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 2~~1~~). This indicates that there ~~is~~ may well be 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 2~~1~~. This assumption allows us to derive the upper and lower limit of the likely TSLS range by fitting a lines to the corresponding limit of sea level projections. Similarly, we assume covariance between the elicitation derived uncertainties of the two warming scenarios.

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 2~~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 do~~es~~ not account for uncertainties in the e.g. climate sensitivity. The cumulated emission and temperatures were averaged over the same time intervals.

5~~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 2~~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 2~~1~~, red and blue). The Pearson correlations are above 0.98 with $p<0.001$ in a two-tailed test for both AR5 ($N=15$) and SROCC ($N=9$), where N is three times the number of scenarios as we include the lower, mid, and upper likely estimates from the reports. 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 (PI, TG, and Sat) also show a close relationship to warming (Figure 2~~1~~, black) with a correlation coefficient of 0.998 ($N=3$; $p<0.05$). 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.

6~~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 2~~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 2~~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 2~~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. ~~Accounting~~Adjusting for t~~T~~hese systematic 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 the rate of sea level rise ~~rate~~, it is evident from Figure 2~~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 2~~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 (~~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.

7~~6~~ Conclusion

We define a new Transient Sea Level Sensitivity (TSLS) metric, which relates the rate of global mean sea level rise to global century-long mean surface temperature change. We find that this metric can account for most of sea level response to temperature increase on ~~a hundred-year~~this 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, e.g. different radiative forcing. 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 propose that TSLS estimated from hindcast simulations~~s~~ can serve as a valuable emergent constraint of sea level models, although this is currently hampered by the lack of information needed to construct these.

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 2~~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) differs. 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 2~~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 the time evolution of 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 what is referred to as the 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.

Acknowledgements

Aslak Grinsted received funding from Villum experiment OldNoble grant number 28024, and Villum Investigator Project IceFlow grant number 16572. This work also received support by the European Union under the Horizon 2020 Grant Agreement 776613, the EUCP project.

References

Ablain, M., Meyssignac, B., Zawadzki, L., Jugier, R., Ribes, A., Spada, G., Benveniste, J., Cazenave, A., and Picot, N.: Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration, Earth Syst. Sci. Data, 11, 1189–1202, https://doi.org/10.5194/essd-11-1189-2019, 2019.

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., & Cooke, R. M.. Ice sheet contributions to future sea-level rise from structured expert judgment. Proceedings of the National Academy of Sciences, 116(23), 11195-11200, 2019.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Clark, P. U., Mix, A. C., Eby, M., Levermann, A., Rogelj, J., Nauels, A., & Wrathall, D. J., Sea-level commitment as a gauge for climate policy. Nature Climate Change, 8(8), 653-655, 2018.

Dangendorf, S., Marcos, M., Wöppelmann, G., Conrad, C. P., Frederikse, T., & Riva, R., Reassessment of 20th century global mean sea level rise. Proceedings of the National Academy of Sciences, 114(23), 5946-5951. doi:10.1073/pnas.1616007114, 2017.

DeConto, R. M., & Pollard, D., Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591, 2016.

Edwards, T. L., et al., Revisiting Antarctic ice loss due to marine ice-cliff instability. Nature, 2019, 566.7742: 58.

Foster, G. L., & Rohling, E. J. (2013). Relationship between sea level and climate forcing by CO2 on geological timescales. Proceedings of the National Academy of Sciences, 110(4), 1209-1214, 2019.

Frederikse, T., Landerer, F., Caron, L. et al. The causes of sea-level rise since 1900. Nature 584, 393–397 (2020). doi:10.1038/s41586-020-2591-3

Grinsted, A., Moore, J. C., & Jevrejeva, S. (2010). Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Climate dynamics, 34(4), 461-472. doi:10.1007/s00382-008-0507-2.

IPCC, Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], 2013.

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., Rahmstorf, S., Temperature-driven global sea-level variability in the Common Era. Proceedings of the National Academy of Sciences, 113(11), E1434-E1441, 2016.

Li, C., von Storch, J. S., & Marotzke, J. (2013). Deep-ocean heat uptake and equilibrium climate response. Climate Dynamics, 40(5-6), 1071-1086.

Mastrandrea et al., Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties (IPCC, New York, 2010), 2010.

Meinshausen, M., Smith, S.J., Calvin, K. et al., The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109, 213 (2011). doi:10.1007/s10584-011-0156-z, 2011.

Mengel, M. et al. Future sea level rise constrained by observations and long-term commitment. Proc. Natl. Acad. Sci. USA 113, 2597–2602, 2016.

Morice, C.P., Kennedy, J.J., Rayner, N.A. and Jones, P.D., Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 dataset. Journal of Geophysical Research, 117, D08101, doi:10.1029/2011JD017187, 2012.

Oppenheimer et al., Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities, Chapter 4 in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (eds.)], 2019.

Rahmstorf, S., A semi-empirical approach to projecting future sea-level rise. Science, 315(5810), 368-370, 2007

Warrick, R. A. & Oerlemans, H. in Climate Change, The IPCC Scientific Assessment (eds Houghton, J. T., Jenkins, G. J. & Ephraums, J. J.) 257–281 (Cambridge Univ. Press). 1990.

Slangen, Aimée B. A., Benoit Meyssignac, Cecile Agosta, Nicolas Champollion, John A. Church, Xavier Fettweis, Stefan R. M. Ligtenberg, et al. “Evaluating Model Simulations of Twentieth-Century Sea Level Rise. Part I: Global Mean Sea Level Change.” Journal of Climate 30, no. 21 (November 2017): 8539–63. https://doi.org/10.1175/JCLI-D-17-0110.1.

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]	$-0.14^{\dagger}$ [-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]

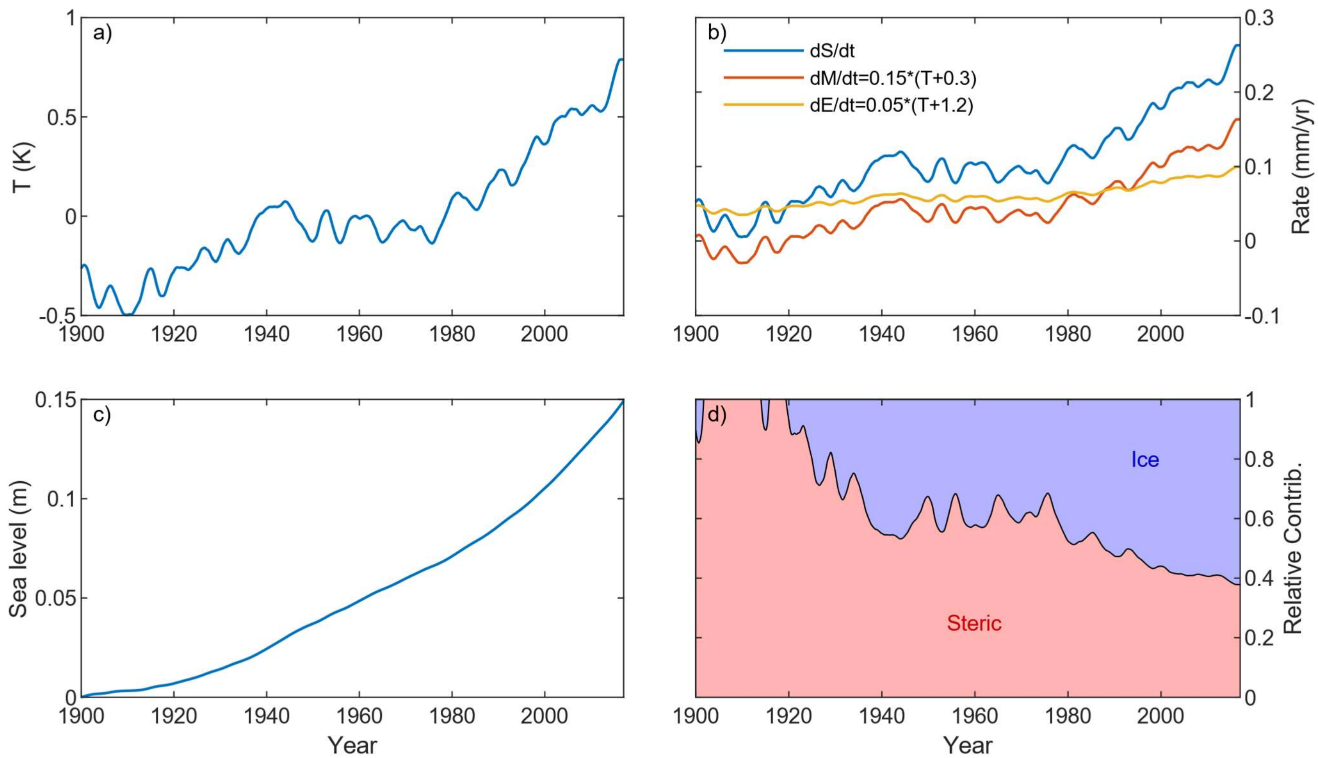

Figure 1: Illustrative example demonstrating how changing relative sea level contributions can arise in a world where all contributors respond linearly to temperature. a) temperature forcing; b) The rate of sea level rise ($\dot{S}$) is modelled as the sum of two contributors: ice melt ($\dot{M}$) and steric expansion ($\dot{E}$); both contributions are modelled as linear in T. c) The sea level curve obtained by integrating $\dot{S}$. d) The relative contributions from ice melt and steric expansion (e.g. $\dot{E}/\dot{S}$).

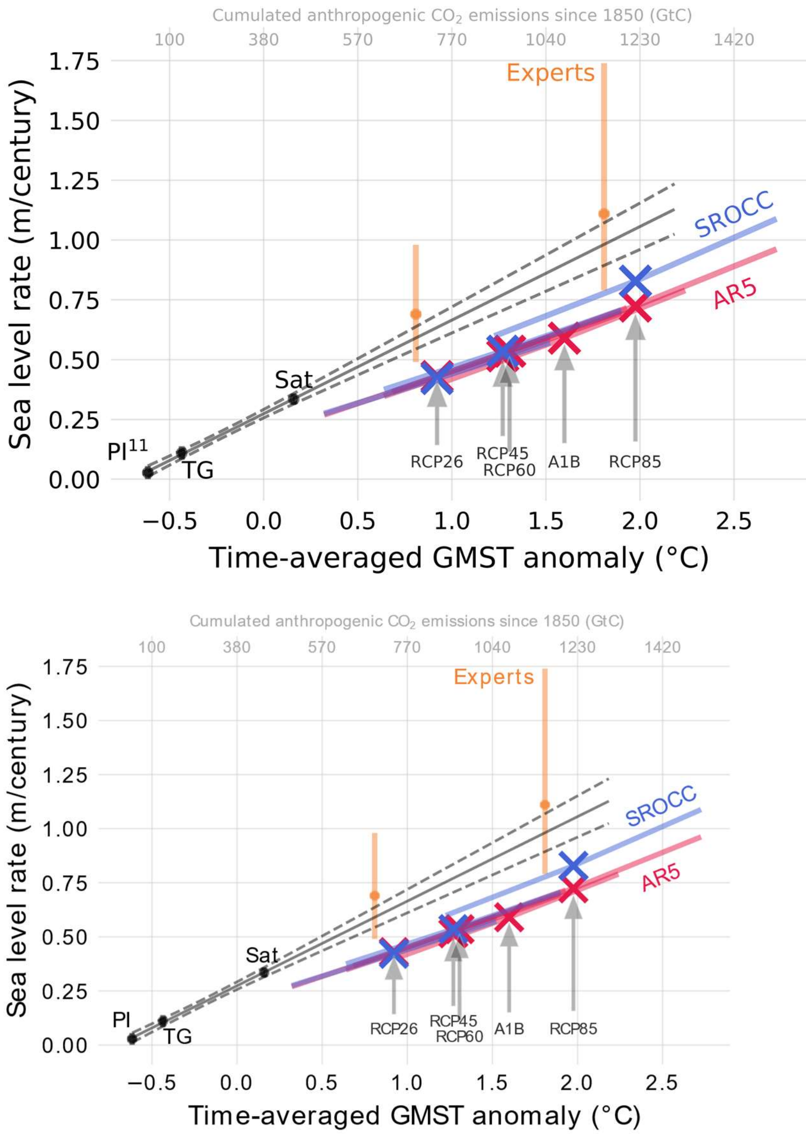

Figure 2~~1~~: The rate of sea level rise versus long term average temperature as seen in observations (black), in model projections (red/blue), and expectations in an expert elicitation (orange). Each point represents an average over a time period (PI: 1850-1900; TG: 1900-1990; SAT: 1993-2017; AR5/SROCC/Experts: 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.