THE SOLAR AND SOUTHERN OSCILLATION COMPONENTS IN THE SATELLITE ALTIMETRY DATA: MODELING THE SEA LEVEL WITH AN ALTERNATIVE MODEL

1. INTRODUCTION

In the main manuscript we used an empirical fit to describe the ocean heat content and sea level change, while approximating the solar forcing as harmonic. The results of that fit were studied using two model, one is a very simplistic and includes only the zeroth order steric component (essentially neglecting the climate feedback) and the dominant eustatic component (arising from water accumulation in slow to equilibrate reservoirs on land). The second is more elaborate in that it models the diffusion of heat into the deep ocean and climate feedback. It also allows for a fast eustatic component (describing water in fast to equilibrate reservoirs). It was found that the more detailed description yields almost the same result, i.e., that the higher order terms are small. Here we utilize a different approach. We use a proxy for the actual solar activity instead of a harmonic approximation, and instead of modeling the climate, we describe the sea level using generic processes that depend on the heat flux, its time integral and double integral. It allows for more "ignorance" of the physical processes, but shows that the main conclusions remain essentially the same.

2. ADDITIONAL DATASET

As in the main manuscript, we use the TOPEX/Poseidon and Jason satellite altimetry missions (Nerem *et al.* , 2010). We also use the NINO 3.4 index to describe the El Niño oscillation (Trenberth, 1997).

Unlike the aforementioned models, here we will use a direct proxy of solar activity. There are several options to choose from including the total solar irradiance (TSI), solar sunspot number, geomagnetic AA index or cosmic ray flux (CRF) to name a few. We checked the aforementioned options and found that using the cosmic ray flux proxy resulted in a slightly better fit, one which is not statistically significant. Thus, the results we describe below are based on the cosmic ray flux proxy, but one should bare in mind that the similar fits imply that one cannot prove or disprove a particular solar climate link (e.g., through cosmic ray flux modulation).

Specifically, we use the Oulu neutron monitor data set (Ahluwalia & Ygbuhay, 2013)[1], which corresponds to an effective rigidity of 5.5 GV (Alanko *et al.* , 2003). Note that we do not use the standard Climax data set since its publication has stopped in 2006.

Since we are interested only in variations longer than the annual time scale, all the three data sets where averaged with a 1-year moving average. The averaged datasets are depicted in fig. 1.

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[1] The actual dataset is retrieved from http://cosmicrays.oulu.fi/.

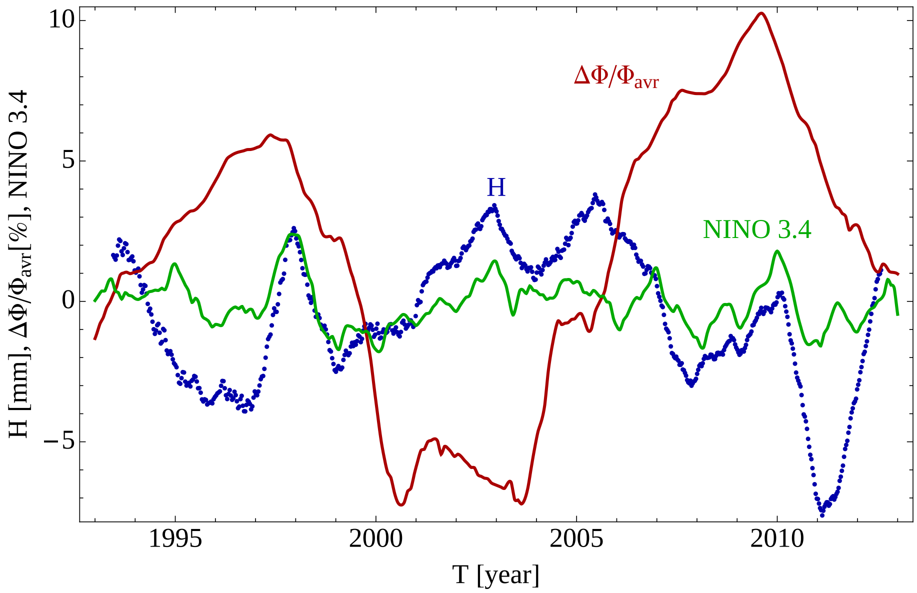

Figure 1: The datasets used in the analysis smoothed with a 1-year moving average. Plotted are annual averages of the the TOPEX and Jason altimetry data, the NINO 3.4 southern oscillation index and the Oulu neutron monitor dataset. The later is plotted as a percent difference from the average.

3. THE GENERIC MODEL

As mentioned in the introduction above, we construct a generic model which includes a more realistic proxy for the solar activity. The model also employs a generalized generic form, instead of constructing simplified physical models for the heat transfer and sea level variations as done in the main manuscript. We assume here that the sea level can be described in the form

$$\begin{aligned} h(t) &= h_0 + h_1(t-t_0) + h_2(t-t_0)^2 \\ &\quad + a_1\Phi_I(t) + a_2\Phi_{II}(t) + b_0 S_{3.4}(t) + b_1 S_{I,3.4}(t) + b_2 S_{II3.4}(t), \end{aligned} \tag{1}$$

were in addition to $S_{I,3.4}$ defined in the main text, we also define:

$$\Phi_I(t) \equiv \int_{t_0}^{t} \Phi(t')dt' - \left\langle \int_{t_0}^{t} \Phi(t')dt' \right\rangle, \tag{2}$$

$$\Phi_{II}(t) \equiv \int_{t_0}^{t} \Phi_I(t')dt' - \left\langle \int_{t_0}^{t} \Phi_I(t')dt' \right\rangle, \tag{3}$$

$$S_{II,3.4}(t) \equiv \int_{t_0}^{t} S_{I,3.4}(t')dt' - \left\langle \int_{t_0}^{t} S_{I,3.4}(t')dt' \right\rangle. \tag{4}$$

t_0 is an arbitrary reference point, chosen for convenience to be 2000 yr. We also normalize $\Phi(t)$ such that $\left\langle \int_{t_i}^{t_f} \Phi(t')dt' \right\rangle = 1$

We first note that the radiative forcing is not uniquely defined up to an additive constant. When integrated twice, it will translate into an unknown quadratic behavior, which is the origin of the h_2 term above. It will imply that the climate system over the considered period is not in radiative equilibrium.

The a_1 and b_1 terms describe the sea level change associated with the absorbed heat from either the solar forcing or a forcing related to the southern oscillation, in particular, through thermal expansion. The heat absorbed could then have secondary effects through feedbacks that will depend on temperature, which roughly depends on the integrated heat content. We therefore add the a_2 and b_2 terms which depend on the integrated heat content, i.e., a double integral of the radiative forcing.

Unlike the solar forcing, the Southern oscillation can have a direct impact on the sea level (without any integration), simply due to the fact the oscillation mixes water at different temperatures and thus changing the net thermal expansion (because the water expansion coefficient is not linear in temperature). Thus, the above fit includes the b_0 term.

4. MODEL RESULTS

A χ^2 fit is carried out to minimize the difference between the model fit and the observed sea level data. For the optimal parameters, the model explains 81% of the 9.3mm^2 variance in the annually averaged quadratically de-trended altimetry data, leaving a 1.72mm^2 residual. This residual is 9% smaller than the residual obtained with fit described in the text, though it does include 8 instead of 6 parameters. With only the solar component, 60% of the variance is explained, while it is 35% with only the ENSO component. Note again that because of some correlation between the southern oscillaton and solar components, the sum of the two contributions is larger than the variance explained by both components combined.

We also note that by using the TSI as a proxy for solar activity, the model explains 78% of the 9.3mm^2 variance, i.e., slightly worse than the cosmic ray flux fit, but not at any significant level.

Table 1: Fit Parameters for the generic model (described in eq. 1).

Parameter	value
h_0	14.5 ± 0.5 mm
h_1	3.30 ± 0.08 mm/yr
h_2	0.02 ± 0.02 mm/yr^2
a_1	-16.5 ± 3.8 mm/yr per relative change in Oulu CRF
a_2	6.1 ± 1.8 mm/yr^2 per relative change in Oulu CRF
b_0	1.57 ± 0.25 per $S_{3.4}$ unit
b_1	0.2 ± 0.4 mm/yr per $S_{3.4}$ unit
b_2	1.0 ± 0.4 mm/yr^2 per $S_{3.4}$ unit

5. IMPLICATIONS OF THE FIT PARAMETERS

A study of fig. 3 reveals that the two solar terms in eq. 1 are comparable, with the integral of the flux (i.e., the a_1 term) being somewhat larger than the double integral term (a_2). As mentioned above, the first term is expected from thermal expansion due to the absorbed heat (a steric component) and a fast to equilibrate change in the total water in the oceans (a eustatic component). The second term arises

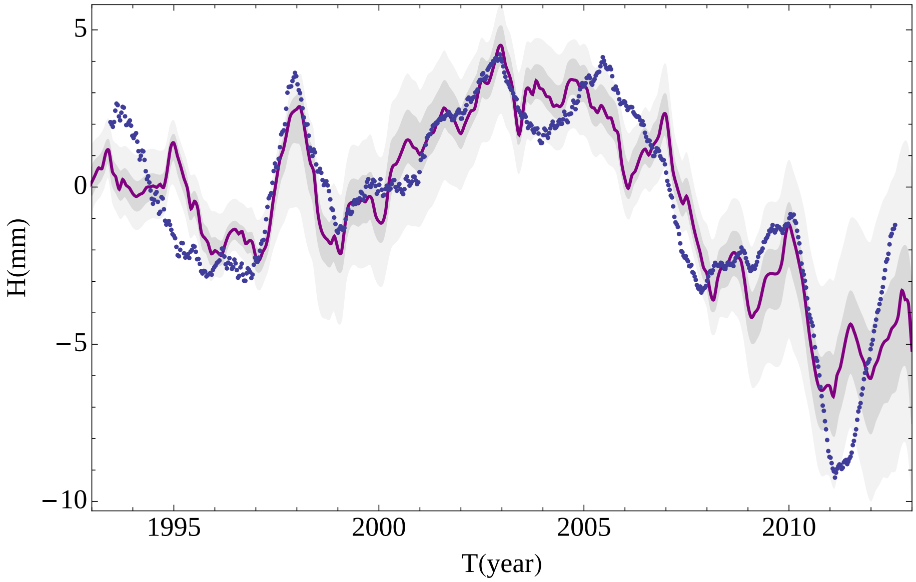

Figure 2: Sea level data and fit using the generic model. The blue dots are the de-trended global sea level measured with satellite altimetry (with the h_i terms of eq. 1 removed). The purple line is the generic model fit to the data which includes both a solar contribution which is assumed to depend on the cosmic ray flux and an ENSO contribution. The shaded regions denote the one σ and 1% to 99% confidence regions. The fit explains 81% of the variance in the detrended data.

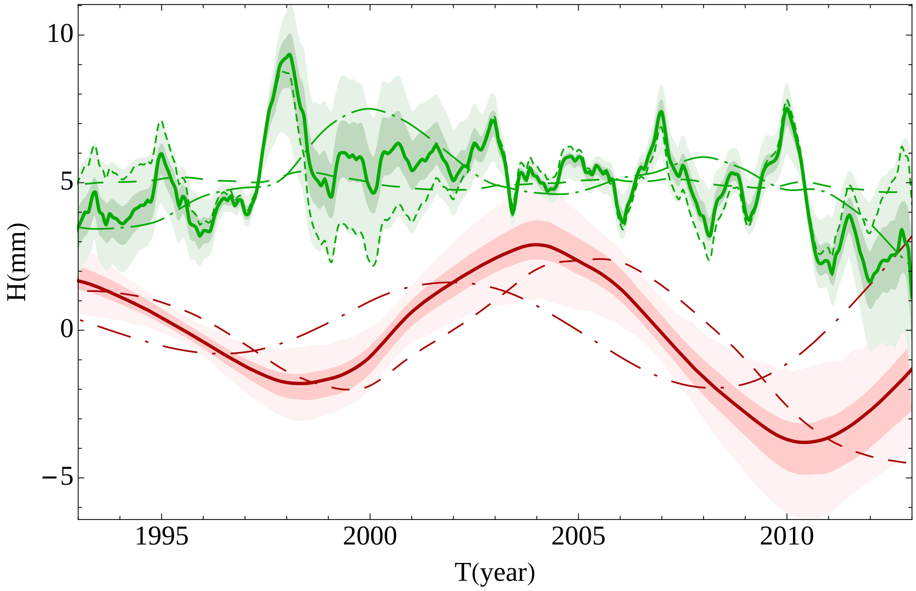

Figure 3: The ENSO (in green) and Solar (in red) contributions in the model fit. The shaded regions denote the one σ and 1% to 99% confidence regions. The thinner lines denote the different terms. For the ENSO, short dashed depicts the b_0 term, dashed the b_1, and the long-short dashing, the b_2 term. For the Solar, the dashed line denotes the a_0 term, while the dash-dotted denotes the a_1 term.

from water trapped on land in slow to equilibrate reservoirs, but could also arise from radiative feedback through a changing oceanic surface temperature.

5.1 The a_1 term

Because the a_1 term is governed by the heat absorbed into the oceans and thermal expansion, it can be used as a calorimeter to measure the radiative flux associated with the solar cycle. However, it is "contaminated" by the fast eustatic component, of a changed amount of water circulating in fast reservoirs (i.e., the atmosphere and surface water). We therefore have to consider both components.

5.1.1 Steric contribution to a_1: The thermal expansion coefficient of water is temperature dependent, one therefore requires the average temperature of the oceans and the assumptions that the oceans heat uniformly. The ratio α between the ocean heat content variations and the sea level change rate can be derived in two ways (Shaviv, 2008). First, if one averages the temperature of the mixed layer, one finds through the temperature dependent thermal expansion coefficient that $\alpha_{steric} = 1.35\ (mm/yr)/(W/m^2)$. Second, one can compare measured temperature variations to measured ocean heat content variations on somewhat longer time scales (Levitus & Boyer, 1994; Ishii *et al.* , 2006) and obtain $\alpha_{steric} = 1.95 \pm 0.2\ (mm/yr)/(W/m^2)$. We will take the average as our nominal value, but use the difference to estimate the error, that is, we take

$$\alpha_{steric} = 1.65 \pm 0.3\ \frac{mm/yr}{W/m^2}. \tag{5}$$

5.1.2 Eustatic contribution to a_1: A second component relating Q and h is an indirect eustatic component. If the oceans absorb heat and increase their temperature, the atmosphere will contain more water vapor and the amount of water circulating over land will increase as well. If the residency time of water in the "fast" reservoirs is constant, the amount of water will increase in proportion to the absolute increase in the water vapor. Over the solar cycle, the peak to peak ocean surface temperature changes by about 0.08°C (e.g., Shaviv, 2005, and references therein). From Clausius-Clapeyron equation, the *relative* change in the *absolute* humidity due to the observed oceanic temperature change is $f = 0.5\%$. This assumes that the atmosphere keeps a constant relative humidity.

The water reservoirs that equilibrate on time scales shorter than a year include the atmosphere, soil moisture, rivers, and biological water. According to Shiklomanov (1993), they add up to $V_{1,\mathrm{eustatic}} \approx 165\ \mathrm{km}^3$. Given the relative change in the absolute humidity over the solar cycle, the sea level should change by $\Delta h_{1,\mathrm{eustatic}} \approx \Delta V_{1,\mathrm{eustatic}}/A_{\mathrm{oceans}}$ where $\Delta V_{1,\mathrm{eustatic}}$ is the net volume change due to the fast eustatic variations over the solar cycle while A_{ocean} is the ocean surface area. We therefore obtain $\Delta h_{1,\mathrm{eustatic}} \approx f V_{1,\mathrm{eustatic}}/A_{\mathrm{oceans}} \approx -0.5$ mm. The sign is negative because increased oceanic heat implies that more water circulates outside the oceans and the sea level is lower. From comparison to fig. 3 it is evident that this component is small, of order 10%.

5.1.3 Implication of combined terms: The full a_1 can now be written as the sum of the two terms described above, such that the peak to peak sea level variation associated with the a_1 term is

$$\Delta h_1 = a_1 \Delta\Phi_I \approx a_1 \frac{P\Delta\Phi}{2\pi} \approx \frac{\alpha P}{2\pi} \Delta F_{\text{solar}} + \Delta h_{1,\text{eustatic}}, \tag{6}$$

where $\Delta\Phi_I$ is the peak to peak variation in $\Phi_I(t)$ over the solar cycle. The expression also assumed that the solar variations can be approximated as harmonic, such that if we write $\Delta\Phi$ as the peak to peak variation in $\Phi(t)$, then $\Delta\Phi_I \approx P/(2\pi)\Delta\Phi$, where $P \approx 12.6$ yr.

The solar radiative forcing over the solar cycle is therefore given by

$$\Delta F_{\text{solar}} \approx \frac{a_1 \Delta\Phi}{\alpha} - \frac{2\pi}{\alpha P} \Delta h_{1,\text{eustatic}} = 1.25 \pm 0.35 \text{ W/m}^2. \tag{7}$$

5.2 The a_2 term

Like before, we can expect the a_2 term to have both steric and eustatic components. However, with the phase lag from the corresponding contributions to the a_1 term, the meaning will be different.

5.2.1 Steric contribution to a_2: The phase lag of the a_2 term implies that any steric contribution to it is not due to direct solar forcing, but instead from feedback through the oceanic response. We can estimate how large it could be by using the observed sea surface temperature variations and a realistic range for the ocean feedback parameter.

The sea surface temperature is observed to have a component in sync with the solar variation. Its peak to peak amplitude is about 0.08°C (see Shaviv 2008 and references therein).

This temperature response can be translated into a radiative forcing through the ocean feedback. The latter is related to the ocean temperature sensitivity—any change in the radiative forcing gives rise to a changed temperature required to balance the radiative imbalance. A sensitive climate will require the oceans to have a large change in the temperature to do so. A very conservative range is an ocean temperature that increases by $\Delta T_{\times 2} = 1 - 5$°C for CO$_2$ doubling. If the latter corresponds to a radiative forcing of $\Delta F_{\times 2} \approx 3.7\,\text{W/m}^2$ (Myhre *et al.* , 1998), then the feedback parameter is $\lambda = \Delta F_{\times 2}/\Delta T_{\times 2} \approx (0.75 - 4)(\text{W/m}^2)/°\text{C}$.

Given this feedback, the above 0.08°C temperature variations should correspond to forcing of about $\Delta F_{\text{feedback}} \approx (0.05 - 0.3)\ \text{W/m}^2$. With the results of §5.1.1, this can be translated into peak to peak sea level variations, which are:

$$\Delta h_{2,\text{steric}} \approx \frac{P a_1}{2\pi} \Delta F_{\text{feedback}} \approx 0.6 \pm 0.4 \text{ mm}. \tag{8}$$

Note that because the feedback acts to counter the effect of the radiative forcing, it is in opposite sign to the forcing.

5.2.2 Eustatic contribution to a_2: Unlike fast eustatic component which cannot be large because the total amount of fast reacting water reservoirs (such as the atmosphere) is small, the amount of water trapped in slow reservoirs (such as glaciers) is unlimited. However, because these reservoirs are slow, their derivative depends on the amount of heat in the oceans, such that they lag behind the integrated heat absorbed in the oceans.

To estimate the size of this component, we can use the fitted a_2 term, and subtract from it the steric component found above. Like the radiative feedback and the fast eustatic components, its sign should be opposite of the radiative forcing. This is because increased oceanic heat increases the evaporation allowing more water to be trapped in reservoirs.

From fig. 3, the peak to peak variations in the a_2 term is roughly 3.6 ± 0.6 mm. If we subtract from it the steric component of 0.6 ± 0.4, we find that the slow eustatic component is

$$\Delta h_{2,\mathrm{eustatic}} \approx 3.0 \pm 0.7 \mathrm{~mm}. \tag{9}$$

5.3 Calorimetric Efficiency

If we compare the sea level variations obtained from the direct radiative forcing of eq. 7, to the additional steric and eustatic components, then we can estimate the calorimetric efficient as the ratio between the direct steric sea level variations and the total sea level variations over the solar cycle. It is $\epsilon \approx 0.70$.

6. DISCUSSION

As with the fit carried out in the main manuscript, we find that the sun and the ENSO are by far the dominant drivers of sea level change on the annual to decade time scale. If the linear or quadratic trends are removed, the two drivers explain about as much as 81% of the variance of the annually averaged data.

We found that the present model fit is better than the fit carried out in the main text. This is probably due to the larger number of free parameters we have here (8 vs. 6), and not because we used an actual solar activity proxy instead of a harmonic approximation. That is because the a_1 and a_2 terms through which the solar forcing enters the model resemble the harmonic oscillation to begin with (see the dashed red curves in fig. 3). This is also why employing other solar forcings (such as the TSI) do not give fits which are any different from that obtained using the CRF.

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