Response to Reviewer 2

Reviewer 2's <u>comment</u>:
The paper is presenting a very good overview of works on sea level rise.
It could be complete if the authors introduce a small discussion on the little glacial era (see the lines 78 – 82 of the introduction) and also the so called Munk enigma.
A key study is presented in a paper by Walter Munk published in 20021. Its importance is lying on the careful analysis made on causes and effects, as in schematised in Figure 1. 1
It is a seminal study since is obliging researcher to give attention to all factors influencing sea level.
Studies were demonstrating that after the little ice age early in the 19th century, sea level rose at 18 cm/century (cm/cy - the historic rate) with no measurable acceleration until the mid-20th century, when thermal expansion associated with greenhouse warming became significant, contributing an additional 3 cm by the year 2000. Greenhouse-related sea level rise has accelerated to the present rate of 6 cm/cy, making the historic + greenhouse rate 24 cm/cy (Figure 4.2.1A). The relative heat content between the sea surface and 3000 m depth (Figure 2B) and the global temperature changes2 (Figure 4.2.1C) are providing the base for the calculation of a steric sea level rise by 12 cm/cy, as represented by the line AB.

Munk addressed the attention of researchers to the IPCC 2001[3] rate of sea level rise that was composed by the sea level in 2000 referred to 1900 (21 cm), the greenhouse contribution (3 cm) and the 'best estimate' of eustatic contribution (6 cm):
3
$\zeta - \zeta_{greenhose} - \zeta_{eustatic} = 21 - 3 - 6 = 12$ cm
rise unaccounted for (the Munk sea level rise enigma)!
It can be published after the revision suggested by the referee and additional text related to the above comments.

<u>Response:</u>

We thank Reviewer 2 for his comment about the Munk's enigma.

Munk's paper was very popular when it was published. However at that time (16 years ago), limited information was available about the components of the sea level budget. Following Munk's original paper, Mitrovica et al. 2006) proposed an improved theory of rotational stability of the Earth, effectively removed the constraints proposed by Munk (2002). This theory allows a polar ice sheet contribution to 20th century sea-level rise of as much as ~1.1 mm/yr, with about 0.8 mm/yr beginning in the 20th century. In addition, since then, recent re-estimates based on tide gauges of the 20th century sea level rise suggest that the 20th century rate could have been lower than assumed in Munk's paper. Moreover, new studies by Gregory et al. (2013) and Slangen et al. (2017) based on observations and models, show that the 20th century sea level budget can be approximately explained within uncertainties.

We extract below a few sentences from these two articles.

Extract from Gregory et al., 2013:

"Considering the twentieth century as a whole, Munk (2002) described GMSLR as an "enigma": it began too early, it had too linear a trend, and it was too large. The first two problems relate to an expectation, based on a general understanding of the processes concerned, that in a warmer climate the rates of thermal expansion and of glacier mass loss will tend to increase. Therefore, we might suppose that these climate-related contributions to GMSLR increased during the twentieth century.
However, the trend of GMSLR during recent decades was actually not very much larger than during the twentieth century as a whole. For instance, Church and White (2011) find 1.9 +/- 0.4 mm/yr for 1961–2009 and 1.7 +/- 0.2 mm/yr for 1900–2009. The third problem, of GMSLR being too large, is shown by the model-derived estimates of contributions reported by Church et al. (2001), which could explain only 50% of twentieth century GMSLR. To balance the budget and explain the form of the time series requires time-dependent information about the contributions to GMSLR throughout the century. We are enabled to make progress by new work summarized in this paper (Gregory et al., 2013) regarding the contributions from thermal expansion, glaciers, the Greenland ice sheet, groundwater depletion, and reservoir impoundment."

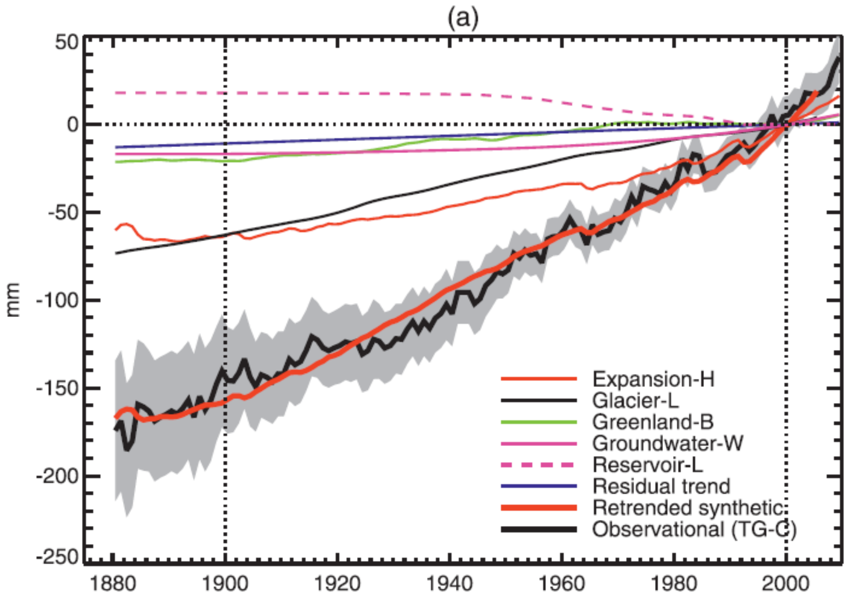

Figure from Gregory et al. (2013) showing closure of the 20tth century sea level budget.

Extract from Slangen et al., 2017:

"In recent decades, one of the major questions in sea-level research has been the closure of the 20th century (global mean) sea-level budget (Munk 2002; Gregory et al. 2013a). There are two parts to this question: firstly, the sum of the observations of the individual contributions tend to underestimate the total observed change, raising the issue of different types of uncertainties in the observations. Secondly, the sum of model-based sea-level contributions tend to underestimate the total observed change for the 20th century, probably due to a combination of uncertainties/imperfections in both models and observations. The observations of total sea-level change and the individual contributions are spatially and temporally sparse, difficult to quality-control, and biased to the Northern Hemisphere (and therefore perhaps not representative of GMSL, Thompson et al. 2016), until satellite data started to become available in the early 1990's. The model-based contributions on the other hand, may not fully account for all climate variability, such as multi-decadal variations in the ocean or the delayed response of glaciers and ice sheets to externally-driven climate change.

A couple of years ago, a large community effort (Gregory et al. 2013a) explored a wide range of observational estimates of all contributions to sea-level change, and managed to close the observational budget to within uncertainties. In this paper we will focus on the second part of the problem, namely at reconciling the summed model estimates with total observed GMSL change. This is an important topic, as a better understanding of and ability to model past sea-level change increases confidence in the models' ability to project future sea-level changes."

Response to Reviewer 2 (continued):

In the revised version, we added a few lines about the 20th century sea level budget.

Lines 113 to 118 of the revised manuscript:

"For example, Munk (2002) found that the 20th century sea-level rise could not be closed with the data available at that time and showed that if the missing contribution were due to polar ice melt, this would be in conflict with external astronomical constraints. The enigma has been resolved in two ways. Firstly, an improved theory of rotational stability of the Earth effectively removed the constraints proposed by Munk (2002), and allows a polar ice sheet contribution to 20th century sea-level rise of as much as ~1.1 mm/yr, with about 0.8 mm/yr beginning in the 20th century. In addition, more recent studies by Gregory et al. (2013) and Slangen et al. (2017), combining observations with model estimates, showed that it was possible to effectively close the 20th century sea level budget within uncertainties."

As a result of these two areas of progress, we consider that Walter Munk's 'enigma' is now effectively solved.