OBSERVATIONS OF THE RATE AND ACCELERATION OF GLOBAL MEAN SEA LEVEL CHANGE

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Climate models and basic physical principles project that global mean sea level (GMSL) will increase and the rate of increase will accelerate under anthropogenic climate change (Church et al. 2013). There is now substantial evidence for this in the observational record, which consists of tide gauge measurements, satellite altimeter measurements, and, indirectly, satellite gravity measurements. Both tide gauge sea level reconstructions and satellite altimetry show that the current rate of global mean sea level change is about 3 mm yr^{-1}, and both show that this rate is accelerating. Usually, this change in the rate of sea level rise is modeled as a quadratic, but other functions (e.g., an exponential) may be equally valid, and in either case one must be careful interpreting these simple functional fits to what are likely to be temporally complex climate responses. Nonetheless, the character of future changes is of enormous socioeconomic consequence.

The tide gauge sea level record is now more than a century long, but it suffers from poor spatial sampling and is sensitive to vertical land motion and coastal effects. In addition, the number of tide gauges decreases dramatically as one goes back in time. Recent papers have argued that the rate of sea level rise as measured by tide gauges during the early part of the century is less than previously understood, perhaps as low as 1.1 mm yr^{-1} over 1900–90 (Hay et al. 2015; Dangendorf et al. 2017), but there is still no consensus on this value due to data quality, estimation, and sampling issues (Hamlington and Thompson 2015; Thompson et al. 2016), with others preferring a value closer to 1.5 mm yr^{-1}. However, over the altimeter era (1992–present), tide gauges show a rate of about 3 mm yr^{-1}, suggesting that global mean sea level has accelerated over the last century (e.g., Merrifield et al. 2009; Church and White 2006), although the tide gauge record also shows higher rates (~2 mm yr^{-1}) in the 1940s. Acceleration estimates averaged over the last century vary from 0.01 to 0.02 mm yr^{-2} (e.g., Dangendorf et al. 2017), but for much of this time period GMSL was probably accelerating very little because ice sheet melt did not start making a substantial contribution to sea level change until the early 1990s (e.g., Bamber et al. 2018). Also decadal variability in the tide gauge record (Haigh et al. 2014), due to both poor spatial sampling and real variability, increases the uncertainty of these estimates. Different analyses of the tide gauge record give different acceleration values depending on the methods used [see Dangendorf et al. (2017) for a summary].

The satellite altimeter record from TOPEX/Poseidon, *Jason-1*, *Jason-2*, and *Jason-3* has observed a rate of sea level rise of ~3 mm yr^{-1} over 1993–2018 (e.g., Nerem et al. 2010; Ablain et al. 2017; Beckley et al. 2017). The satellite altimeter record is short (25 yr) and thus great care must be taken when trying to extract any climate-driven acceleration from variability due to volcanic activity, climate variability (ENSO, PDO, etc.), and interannual variability driven by water storage variations. However, the altimeter record provides nearly global coverage between ±66° latitude (biases due to non-polar coverage are currently small; Lickley et al. 2018). A number of recent papers have detected increases in the decadal rates of sea level change from the altimeter record (e.g., Watson et al. 2015; Chen et al. 2017; Dieng et al. 2017). Fasullo et al. (2016) showed that the eruption of Mount Pinatubo in 1991 had a profound effect on the altimeter GMSL record, causing the rate of sea level rise to be higher in the early part of the record (a negative acceleration over the altimeter era).

For the relatively short sea level records available from satellite altimetry, it is helpful to try to remove different sources of variability to reveal the "climate-driven" sea level changes. Nerem et al. (2018) used a model to correct the altimeter record for the effects of

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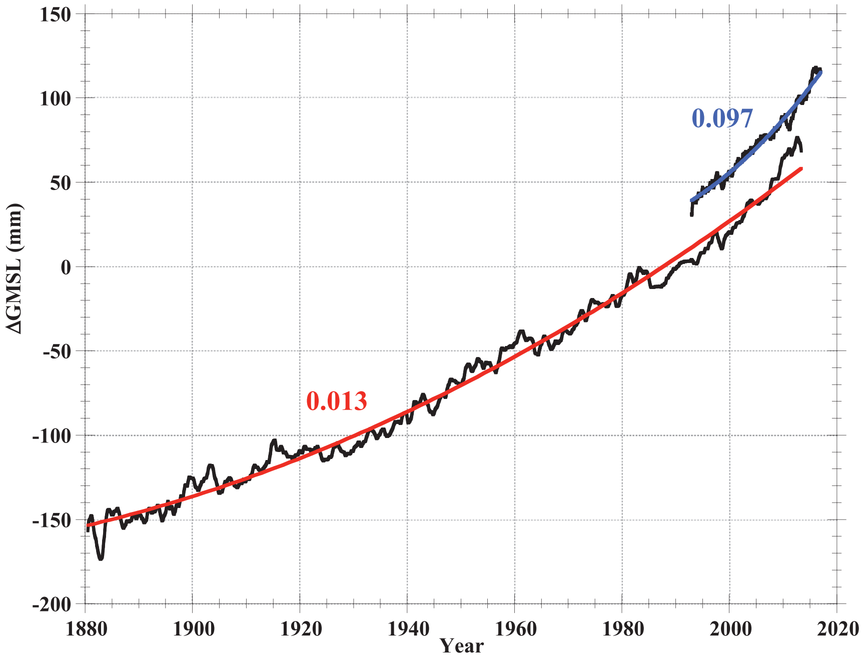

Fig. 1. Global mean sea level variations from a tide gauge sea level reconstruction (Church and White 2011) and satellite altimetry (Beckley et al. 2017) before correcting for Pinatubo and ENSO, with quadratic fits covering 1880–2015 and 1993–2017 respectively. Quadratic fits are summarized in Table 1 [updated from Nerem et al. (2018)]. Curves are offset for readability.

here. Table 1 shows a summary of some of these rate and acceleration estimates. Nerem et al. (2018) also used the gravity record from the GRACE mission (2002–17) to determine that ~45% of the rate and ~90% of the acceleration observed in the altimeter record is due to ice mass loss from Greenland, Antarctica, and mountain glaciers and small ice caps, with the rest being due mainly to thermal expansion.

The closing of the sea level budget for the rate has been a subject of much study and is often the basis for statements of attribution. There is much uncertainty in closing the budget of the tide gauge record (e.g., Jevrejeva et al. 2017), but we have a much better understanding of the altimeter era, largely because of the GRACE mission and the Argo network of profiling floats to measure heat content. Nevertheless, different analyses may give different amounts of attribution (e.g., Dieng et al. 2017). The attribution of the changes in sea level can be directly tied to increases in surface land and sea temperatures, because the changes are due almost entirely to the melting of land ice (Bamber et al. 2018) and increasing heat content of the oceans (leading to

Mount Pinatubo and removed interannual variability due to ENSO and PDO. They found a climate-driven acceleration of 0.084 ± 0.025 mm yr^{-2}, which is comparable to tide gauge estimates post-1970 but higher than them over the last century because for most of the century the ice sheets were largely in balance (Bamber et al. 2018).

Figure 1 shows some of the time series used to determine the rates and accelerations discussed

Table 1. GMSL acceleration estimates from tide gauges and satellite altimetry [updated from Nerem et al. (2018)].

Component	Time period	Rate epoch	Rate (mm yr^{-1})	Acceleration (mm yr^{-2})
Greenland	2002.3–2017.0	2005	0.66	0.0236
Antarctica	2002.3–2017.0	2005	0.19	0.0332
Mountain glaciers and small ice caps	2002.3–2017.0	2005	0.51	0.0094
Thermosteric[1]	1993.0–2016.0	2005	1.65	0.0076
Components total		2005	3.01	0.0738
Altimeter observed	1993.0–2017.0	2005	3.1	0.097
Altimeter observed[1]	1993.0–2017.0	2005	2.9	0.117
Altimeter observed[2]	1993.0–2017.0	2005	2.9	0.084
Tide gauges[3]	1880–2015	1950	1.6	0.012

[1] Corrected for Pinatubo.
[2] Corrected for Pinatubo and ENSO effects (climate change–driven acceleration).
[3] From updated results of Church and White (2011).

thermal expansion). Therefore, most of the observed sea level change is anthropogenic (e.g., Slangen et al. 2016) although a secondary role for internal climate variability also exists (Swart et al. 2015).

As a thought experiment, Nerem et al. (2018) extrapolated the quadratic fit to the altimeter record to 2100 and found 65 ± 12 cm of sea level rise by 2100 relative to 2005, which agrees well with the IPCC AR5 projections (Church et al. 2013). This extrapolation suggests that the rate of sea level rise in 2100 could be ~10 mm yr^{-1}. While extrapolation of this simple functional fit is not a physically based way of projecting future sea level change, it does provide a data-driven method of representing past changes so that they can be compared to climate models. Various physical realizations of twenty-first-century climate change are potentially associated with the range of statistical assumptions and relate in particularly to cryospheric instabilities in Antarctica and Greenland and the estimated range of polar amplification, cloud feedbacks, and climate sensitivity.

On the whole, the available observational evidence suggests that the rate of global mean sea level is accelerating in response to anthropogenic forcing roughly as the climate models have predicted. However, there is still much uncertainty regarding how fast the ice sheets will respond to warming, and what this response will look like over time. As the observational record continues to grow, in part made possible with the launches of *Jason-3* in January 2016 and GRACE-FO in May 2018, and as climate models are coupled to ice sheet models such as in the CMIP6 multimodel ensemble now being generated at major climate centers, the observational record will become increasingly useful for validating models and ultimately reducing the uncertainty in future sea level change projections. While we have focused here on global mean sea level, satellite altimetry also provides the spatial variations of sea level change and these may soon be useful for attribution studies, as the different contributions to sea level change have distinctive regional patterns. In addition, regional estimates of climate-driven sea level change will be more useful for sea level impact studies than the global average.

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