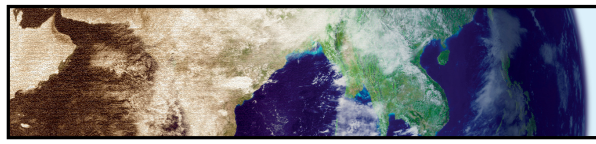

Sea level rise - How much and how fast will sea level rise over the coming centuries?

PRESENT PAST

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Sea level is a sensitive indicator of climate change and responds to global warming both directly and indirectly. It rises as oceans warm up and seawater expands, and also as mountain glaciers and ice sheets melt in response to increasing temperature. Tide gauge measurements available since the late 19th century indicate that the global mean sea level has risen by an average of 1.7-1.8 mm year^{-1} during the 20th century (Church and White 2011), marking the end of the relative stability of the past three millennia. Satellite data available since 1993 point to a higher mean rate of sea-level rise of 3.2±0.4 mm year^{-1} during the past two decades (Cazenave and Remy 2011)

Ocean temperature data suggest that ocean thermal expansion has significantly increased during the second half of the 20th century, accounting for about 30% of the sea-level rise observed since 1993 (Cazenave and Remy 2011; Church et al. 2011a). Numerous observations have reported a worldwide retreat of glaciers during recent decades, with a significant acceleration of this retreat during the 1990s: this also contributes to about 30% of the sea-level rise. Change in land water storage due to natural climate variability contributes negligibly to sea level rise. Human activities (mostly underground water mining and dam building along rivers) have had large effects on sea level during the past six decades or so, but have mostly canceled each other out (Church et al. 2011a).

Little was known before the 1990s on the mass balance of the ice sheets because of inadequate and incomplete observations. But remote sensing techniques available since then suggest that the Greenland and West Antarctic ice sheets are losing mass at an accelerated rate, mostly from rapid outlet glacier flow and further iceberg discharge into the surrounding ocean (Steffen et al. 2010; Pfeffer 2011). For the period 1993-2003, less than 15% of the rate of global sea-level rise was due to the ice sheets. But their contribution has increased to ~70% since 2003-2004. Although not constant through time, mass loss from the ice sheets explains ~25% of the rate of sea-level rise since the early 1990s (Cazenave and Remy 2011; Church et al. 2011a).

There is little doubt that global warming will continue and even increase during the future decades as greenhouse gas emissions, the main contributor to anthropogenic global warming, are likely to keep growing. Projections from the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2007) indicate that sea level in the year 2100 should be higher than today's value by ~40 cm (within a range of ±15 cm due to model results dispersion and uncertainty on emissions). More recently it has been suggested that this value could be a lower bound. This is because the climate models at the time accounted for ocean warming and glacial melting (plus a surface mass balance component for the ice sheets) (IPCC 2007), but not for the recently observed dynamical processes that became quite active during the last decade (Steffen et al. 2010; Pfeffer 2011).

Thus, mass loss from ice sheets could eventually represent a much larger contribution to future sea-level rise than previously expected (Pfeffer 2011). Yet, despite much recent progress in process understanding and modeling, the ice sheet contribution to 21st century sea-level rise remains highly uncertain. Values around 30-50 cm by 2100 cannot be ruled out for the total land ice (glaciers plus ice sheets) contribution. If we add the ocean-warming component (in the range 20-30 cm; IPCC 2007), global mean sea level at the end of this century could eventually exceed present-day elevation by 50-80 cm (e.g. Church et al. 2011b).

Providing realistic sea-level projections remains a high priority in the climate modeling community given their importance to developing realistic coastal management and adaptation plans. But sustained and systematic monitoring of sea level and other climate parameters causing sea-level rise – for example, ocean heat content and land ice melt – is also needed. The better we understand present-day sea-level rise and its variability, the better we will be able to project changes in future sea level.

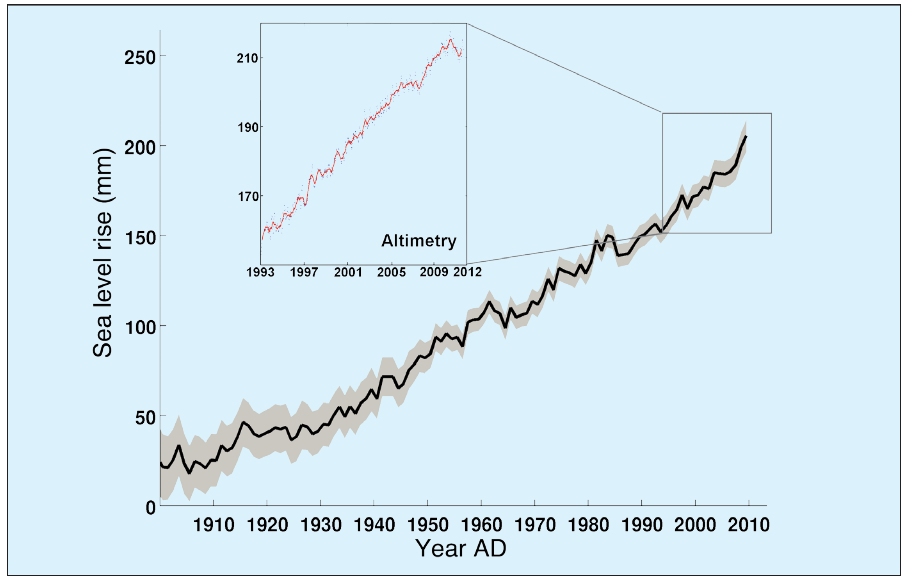

Figure 1: Twentieth century sea level curve (in black and associated uncertainty in light gray) based on tide gauge data and additional information (data from Church and White 2011). Box: altimetry-based sea level curve between 1993 and 2011 (data from AVISO; www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla/index.html). Blue points represent data at 10-day intervals, the red curve their 4-month smoothing (from Meyssignac and Cazenave, unpublished data).

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Full reference list online under:
http://www.pages-igbp.org/products/newsletters/ref2012_1.pdf

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PRESENT **PAST**

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The time scales of major West Antarctic Ice Sheet (WAIS) growth and retreat are centuries to millennia. Instrumental records around West Antarctica are only a few decades long and can therefore only offer a single snapshot of a moving target. The recent observed breakup of some Peninsula ice shelves, and accelerated flow and thinning of their upstream glaciers and Pine Island-Thwaites glaciers (e.g. Shepherd et al. 2003; Pritchard and Vaughan 2007; Jenkins et al. 2010), may be harbingers of future retreat, but by themselves shed little light on potential progression into a full collapse of central WAIS. If anything, contemporary observations indicate ever more pressingly that paleo data are uniquely placed to understand the collapse of the WAIS. Sub-ice shelf warming of part of the WAIS (Jenkins et al. 2010) indicates oceanographic phenomena bringing warm water masses onto the shelf next to the WAIS that may well turn out to be analogous to past collapse events once we understand more fully the processes behind them. It is critical to understand, not just the ice sheet itself, but the oceanography of the Antarctic shelves and sub-ice shelf systems. Oceanic modeling of these systems is challenging, and studies of past and future changes are in early stages of development (e.g. Holland et al. 2008; Olbers and Hellmer 2010; Dinniman et al. 2011). This is where studies such as ANDRILL (Naish et al. 2009) that span the relevant time periods truly come into their own. Such studies have provided substantial evidence from different climate states implying that drastic collapses of marine-based WAIS occurred during the warmest intervals of the Pleistocene and Pliocene. Coupled with related modeling studies (e.g. Pollard and DeConto 2009), these data represent among the best opportunities to understand the potential collapse of the WAIS during past warm periods.

Because of the availability of data, the Last Interglacial (LIG) has become an important target for the question of WAIS stability (e.g. Siddall and Valdes 2011). Estimates of eustatic sea level based on glacio-isostatic modeling of relative sea-level data for the LIG indicate that sea levels approached around 8-9 m above modern (Kopp et al. 2009). At the same time, a number of model-data syntheses have concluded that the maximum contribution to sea level from Greenland was only several meters at most (see Colville et al. 2011 for a recent review) and the contribution from thermal expansion was only in the tens of centimeters (McKay et al. 2011). The gap between the eustatic sea-level rise and plausible Greenland and steric contributions lead to the unavoidable conclusion that the WAIS did indeed reduce dramatically for LIG conditions. Further careful studies may well show more precisely by how much and under what oceanographic conditions this collapse occurred, and whether collapses occurred in earlier Pleistocene interglacials (Scherer et al. 2008; Hillenbrand et al. 2009).

For human populations this issue does not end with the question as to under what conditions will the WAIS begin to reduce dramatically. Two other questions arise – at what rate will it reduce and how will the ice-volume be redistributed in the ocean? Multiple studies of relative sea level during the LIG tentatively suggest rates of sea-level rise of the order of one meter per century resulting from ice sheet reduction beyond that which we have observed in the late Holocene (Rohling et al. 2008; Kopp et al. 2009; Thompson et al. 2011). Glacial isostatic adjustment (GIA) modeling of scenarios regarding the WAIS collapse indicate a 50% variability in local sea-level rise resulting from the collapse of the WAIS (Mitrovica et al. 2009). GIA models have been constructed largely to explain GIA responses since the Last Glacial Maximum and therefore paleo data is crucial to understand if the WAIS will collapse in the coming century, the rate of sea-level rise and its global distribution.

Given the complexity of ice sheet behavior it would be easy to become focused entirely on modern observations and state of the art deterministic models. Here we have argued for the careful, focused use of paleo data to understand the potential for the collapse of the WAIS in the next century and its implications for local populations.

Visite the PALSEA web site for more details:
http://eis.bris.ac.uk/~glyms/working_group.html

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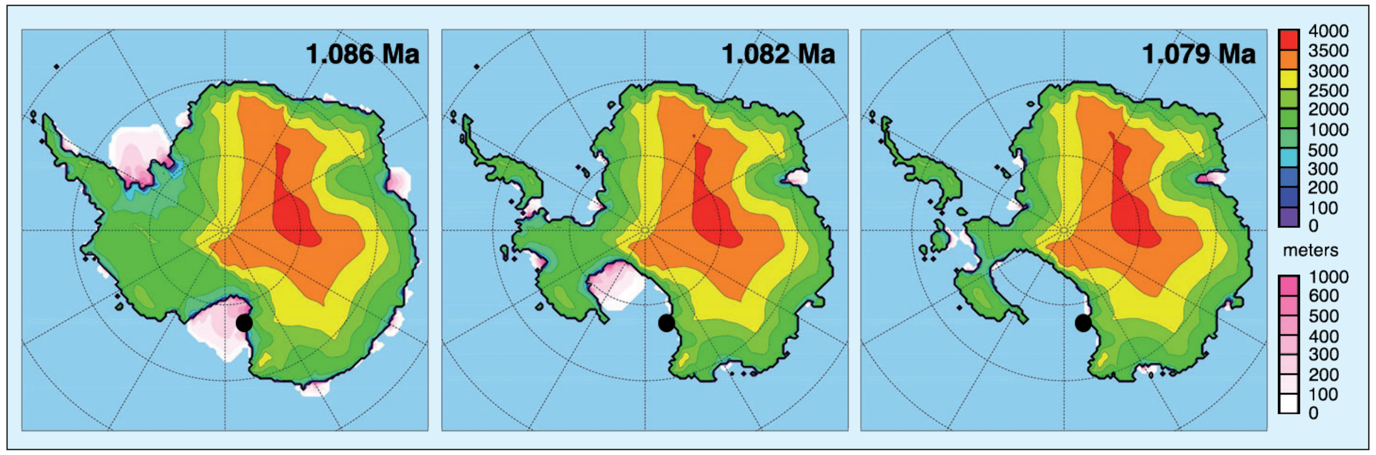

Figure 1: Snapshots of modeled ice distribution, essentially as in Pollard and DeConto 2009, showing collapse of WAIS marine ice leading into Marine Isotope Stage 31, a major interglacial event ca. 1.08 to 1.06 Ma (Scherer et al. 2008; DeConto et al., unpublished data). Grounded ice elevations (m) are shown by the rainbow scale, and floating ice thicknesses (m) by the pink scale. The approximate location of Cape Roberts and ANDRILL sediment cores (Scherer et al. 2008; Naish et al. 2009) is shown by a black dot.