



Sea Level Rise – The State of the Science

Sea level rise is one of the most widespread impacts expected to result from global warming. Scientific understanding of sea level change has progressed significantly in the past few years, especially for past and current sea level rise. For instance, it is now clear that sea level rise accelerated during the 20th century. Projecting future sea level rise, however, is now less certain because of recent, unexpected changes in large polar ice sheets that were assumed to be stable. This fact sheet briefly describes the current state of the science on sea level rise.

General Background

Two primary processes contribute to sea level rise (SLR): 1) **thermal** expansion—the increase in water volume resulting from heat uptake; and 2) **mass** inputs—the transfer of freshwater from land to the ocean. The largest portion of mass inputs is from the loss of land-based ice as warming proceeds. Mountain glaciers at all latitudes, large ice sheets in the polar regions, and frozen soils all can contribute water to the ocean (Houghton et al. 2001).

Large land-based ice sheets in the polar regions represent the largest potential source of additional water mass to the oceans (factor #2 above). There are two general mechanisms by which such ice sheets transfer water to the ocean: 1) melting of ice on land with subsequent runoff into the ocean; and 2) ice dynamics, wherein ice actually flows from land into the ocean; if this flow accelerates, all else being equal, SLR accelerates. Note that when ice is transferred from land to sea, it immediately raises the sea level, like dropping an ice cube into a glass of water. Until recently, ice dynamics were thought to be unchanging (Houghton et al. 2001), but recent evidence strongly suggests that accelerated ice flow into the ocean is underway in both the Arctic and in parts of Antarctica (Alley et al. 2005; Rignot and Kanagaratnam 2006; Thomas et al. 2006; Velicogna and Wahr 2006). These recent dynamical changes have surprised glaciologists, and now the greatest source of uncertainty for predicting future SLR is how large ice sheets will behave in the future as warming proceeds (Alley et al. 2005; IPCC 2007; Gregory and Huybrechts 2006).

The ice sheets on Greenland and West Antarctica store enough water to raise global sea level by about 40 feet if completely released to the ocean. Scientists do not believe that a complete release could happen instantaneously, but even a small portion of this ice released over the span of several decades would generate extreme impacts from SLR for millions of people. Because of this fact and the surprising dynamical changes observed in these ice sheets recently, their potential collapse may be the greatest long-term risk humans face from global warming (Hansen 2005), although there are many serious near-term risks as well, such as more extreme weather events, decreased water supplies, and disruption of many natural ecosystems (McCarthy et al. 2001; IPCC 2007).

Ancient sea level change

Over the past million years, the earth has undergone a repeating cycle of cold ice ages alternating with warm interglacial periods. Over the past four cycles, each lasting about 100,000 years, sea level rose and fell by about 400 feet, with ice ages having lower sea level and warm interglacial periods having higher sea level. Sea level rose as fast as 8 inches per decade during warming events (Siddall et al. 2003). The transfer of freshwater from large land-based ice sheets to the ocean dominated SLR during interglacial warming (Overpeck et al. 2006).

The study of ancient climates reveals a consistent relationship between surface temperature and sea level. During the warmest part of the last interglacial period (about 130,000 years ago), global average temperature was 2-3 °F warmer than it is today, because more solar energy reached the earth's surface in the northern hemisphere (Petit et al. 1999; Petit 2001). At around the same time, global sea level was 13-20 feet higher than it is today, and the Greenland ice sheet was much smaller (Overpeck et al. 2006). During an earlier period about three million years ago (the Middle Pliocene), global temperature was 3.5-5.5 °F warmer than today and sea level was 80-115 feet higher (Rahmstorf 2007; Dowsett et al. 1994). For context, if emissions of man-made greenhouse gases continue without abatement, the earth could warm by 5.5 °F within the next century (IPCC 2007). Although the complete loss of large ice sheets would likely occur over centuries or millennia, warming could cross a threshold within this century beyond which destabilization of the large ice sheets would be irreversible (Hansen 2005; Overpeck et al. 2006; Gregory and Huybrechts 2006).

Recent sea level rise

Based on tide gauges set along coasts around the world, sea level rose by an average of 0.7 inches per decade (Houghton et al. 2001) and accelerated by 0.05 inches per decade over the 20th century (Church and White 2006). Other evidence of recent acceleration is found in the more accurate record of SLR from modern satellites that measure the height of the ocean's surface from space. Such measurements have been available since 1993, so we can only use them to compare the past decade or so with the long-term average from tide gauges. Since 1993, global sea level has risen by 1.2 inches per decade, about 70% faster than the 20th century average (Nerem et al. 2006). Because of the short time span of the satellite record, confirmation of this recent acceleration will require more time, but it is consistent with the changes detected in the longer tide gauge record and recent increases in ocean warming and land-based ice contributions to sea level, as discussed below.

Until recently, scientists assumed that thermal expansion dominated contemporary SLR (Houghton et al. 2001). Recent progress has changed that perception, and it now appears that mass contributions from glaciers and ice sheets dominate, with the latter comprising at least half of total SLR over the past decade (Nerem et al. 2006). Recent measurements of glaciers and ice sheets show increased mass loss (Cazenave 2006), which is consistent with the larger than expected contribution from land-based ice to contemporary SLR. The discovery of a large mass input contribution is one of the most important recent advances in our understanding of SLR.

Projections of Future SLR

Thermal expansion is relatively simple to project using physical climate models. Because the ocean has an enormous thermal inertia, it takes many decades for sea level to adjust to a quantity of heat that it absorbs. This delay means that even if manmade greenhouse gas emissions were completely halted today, sea level rise would be committed to an additional 0.4-1.0 foot by the end of this century (Meehl et al. 2005). Continued global warming would of course generate additional SLR.

Based on estimated thermal expansion and ice melt from glaciers and continental ice sheets, the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-TAR) projected that sea level would rise by 0.3-2.9 feet by the end of the 21st century (Houghton et al. 2001). The new Fourth Assessment Report (IPCC-AR4), published in 2007, projected a narrower range of 0.6-1.9 feet (IPCC 2007). The lower end of this range is only slightly higher than the sea level rise commitment described above and leaves little room for additional contributions from further ocean warming or land-ice mass changes, making such a small amount of 21st century SLR improbable. On the upper end, the uncertainty associated with future dynamical ice changes in

Greenland and West Antarctica was not included, but the IPCC-AR4 states that linear acceleration (a simple extension of recently observed acceleration) of dynamical ice loss could add up to 0.7 feet of sea level rise in the 21st century. This addendum to the projected range still does not account for uncertainty associated with potential amplifying features that could stimulate more rapid, nonlinear acceleration (Alley et al. 2005; Gregory and Huybrechts 2006; Hansen 2005).

Regardless how much SLR occurs during this century, it will likely represent the beginning of a much longer-lasting and larger SLR event: “If a negative surface mass balance [i.e. net ice loss] were sustained for millennia, that would lead to virtually complete elimination of the Greenland ice sheet and a resulting contribution to sea level rise of about 7 m [23 feet]” (IPCC 2007). This assessment does not account for the West Antarctic ice sheet, which holds a similar amount of ice and potentially could become destabilized as well. As stated in the IPCC-AR4, “[u]nderstanding of these processes is limited and there is no consensus on their magnitude” As a result, we know too little today to deem such an event as highly unlikely, as the climate conditions associated with similar past events appear to be within the reach of human-induced global warming over the next century if greenhouse gas concentrations continue to rise (Hansen 2005; Overpeck et al. 2006; IPCC 2007).

Current SLR models undershoot the sea level change observed during the 20th century, possibly because they do not appropriately represent the mass contributions (Rahmstorf et al. 2007). For this reason, a more basic approach to projecting future SLR may be useful for comparison. Rahmstorf (2007) simply quantified the relationship between temperature rise and SLR observed during the 20th century, then extended this relationship through the 21st century, using models of future temperature change to drive SLR (unlike sea level models, temperature models match the observed temperature change of the 20th century quite well). This **empirical** approach estimated 21st century SLR to be in the range of 1.6-4.5 feet, if manmade greenhouse gas emissions continue to grow. The low end of this projection is consistent with the estimated SLR commitment plus a small amount of additional SLR. The higher (relative to IPCC-TAR) upper end is consistent with a large freshwater mass contribution to SLR during the 20th century, recent changes in ice dynamics on polar ice sheets, and the large difference between present sea level and ancient sea levels during warming events similar to projected human-induced global warming.

Conclusions

Over the past few years there has been a great deal of scientific progress in understanding sea level rise. Both tide gauge measurements and recent satellite measurements suggest that SLR accelerated during the 20th century, concomitant with increasing global temperature. Perhaps the most significant development of recent years is the realization that mass contributions from land ice have contributed to contemporary SLR much more than assumed just five years ago. Related to this finding is the fact that large polar ice sheets appear to be much more sensitive to surface warming than previously realized, such that surprisingly large dynamical changes are now being observed on the Greenland and West Antarctic ice sheets. New understanding of how these ice sheets behaved in the past suggests that they could add water mass to the oceans much more quickly than previously assumed, and new empirical projections of SLR for the 21st century are consistent with this analysis. The potential for the rapid collapse of large ice sheets seems more plausible than in the recent past, and some scientists therefore warn that continued anthropogenic warming could result in the start of abrupt sea level rise within the current century.

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