Editorial: Past ice sheet dynamics and sea level—placing the future in context

Mark Siddall[1], William G. Thompson[2] and Claire Waelbroeck[3]

[1]Department of Earth Sciences, University of Bristol, UK; mark.siddall@bristol.ac.uk
[2]Department of Geology and Geophyiscs, Woods Hole Oceanographic Institution, USA; [3]Laboratory of Climate and Environmental Sciences, Pierre-Simon Laplace Institute, Atomic Energy Commissariat, National Centre of Scientific Research, Gif-sur-Yvette, France.

Paleo-evidence can contribute long-term perspective on future sea level/ice sheet change in both a quantitative sense and in the sense of understanding longer-term dynamics (see Abe-Ouchi et al., this issue). This special edition of *PAGES news* led by the PALSEA (PALeo SEA level) Working Group covers recent advances in the field of paleo sea level (see Dutton et al., Andersen et al., and Stirling and Andersen, this issue) and ice sheet reconstruction (see Clark, this issue). The focus is on the application of this data to a better understanding of contemporary and future sea level and ice sheet change, as well as directions for future research.

New questions for paleodata are driven by the limitations of the 'modern-only' approach

Continuing eustatic sea level rise includes contributions from thermal expansion, reductions in glaciers and ice caps, and reductions in polar ice sheets. Although there are important uncertainties in observing and predicting each of these components, the contribution from thermal expansion over the last millennium is relatively well understood (Gregory et al., 2005). Furthermore, the contribution from glaciers and ice caps (and the related uncertainty) is set to decrease over the course of the coming century as these reserves of ice finally disappear. This leaves the ice sheet contribution and its related uncertainties.

Ice sheets are notoriously difficult to understand (Alley et al., 2005). Unlike the biosphere, atmosphere and ocean, ice sheets are solid and opaque and do not lend themselves to direct observation (Fig. 1). Modern observations of ice sheets consist of surface observations and limited observations of processes that occur at the bed, grounding line, and within the ice sheets.

Despite these difficulties, significant advances in observing modern ice sheets have been made over recent decades, in particular with the advent of satellite gravimetric techniques. Evidence from satellite imagery has also been key in documenting the rapid collapse of ice shelves and subsequent acceleration of ice streams in response. However, the short duration of direct observations of ice sheet change (several decades) from satellite observations (<20 years) limits these data to understanding sub-centennial processes (see Bamber, this issue). Key questions, such as the long-term effect of the collapse of fringing ice shelves deep into the ice sheet interior, remain unanswered. Similar limitations apply to the tide-gauge sea level record, which is, at most, several centuries long (Church and White, 2006; Jevrejeva et al., 2008).

Lessons for the future from paleo-archives

In the broadest sense, paleodata informs us that there have not always been significant ice sheets on Earth. Periods without ice sheets had corresponding high temperatures and atmospheric CO_2 concentrations. We know that during the mid-Pliocene warm period sea level was 5 to 40 m higher than today and global temperature was some several degrees warmer (see Raymo et al., this issue). Indeed, during the last interglacial period, global temperature was milder than today and sea level was some 3 to 6 m higher. It is noteworthy that for similar (if not identical) climate conditions to those predicted for the coming centuries, the ice sheets of the past were significantly smaller than today. Colder conditions are linked to larger ice sheets. According to the Paleoclimate Model Intercomparison Project, the Last Glacial Maximum was 3 to 5°C colder than today (IPCC, 2007) and sea level was 120 to 140 m below modern (Fairbanks, 1989; Yokoyama et al., 2000).

As well as providing context for the broad relationship between global sea level and temperature, paleodata gives us perspective on rates of contemporary sea level rise. For example, Flemming et al. (1998) found that sea level rose at an average rate of 0.04 to 0.07 m per century over the last 7 ka. Furthermore, they found a reduced rate of sea level rise over the last 2 ka compared to the period between 7 and 2 ka. This compares with the IPCC estimate over the 20th century based on tide-gauge data of 0.12 to 0.22 m rise, giving a clear indication that contemporary sea level rise is anomalous in the context of late Holocene sea level change. Further, important

Figure 1: Changes in elevation over the Greenland Ice Sheet between 2003 and 2006 from the ICESat elevation satellite. Thickening is shown in ***white*** *and thinning is shown in* ***blue****, while* ***gray*** *indicates no change. Care must be taken in considering the implications of this image—changes in height do not necessarily translate to changes in mass because ice can melt, lose trapped air and refreeze in a denser configuration. The observation of a large, opaque object is inevitably difficult and indirect. Furthermore, the short duration of such observations places limits on the weight one can place on these observations. Paleo sea level and ice sheet reconstructions can help plug some of these gaps. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio. The Next Generation Blue Marble data is courtesy of Reto Stockli (NASA/GSFC).*

lessons can be learnt by studying evidence for Holocene sea level and ice sheet change in the context of regional climate change, such as the Medieval Warm Period and the Little Ice Age (see Kelly and Long, and Yu et al., this issue). In turn, Holocene changes must be considered in the light of the large changes in ice volume and sea level during the termination of the last glacial period (T1). During T1, the interaction between ice sheets, ocean circulation and global warming greatly perturbed the ice sheets and can be regarded as a case study for large changes in global climate on decadal to centennial timescales (see PALSEA, 2009). In particular, relative sea level variations during this period may help reveal which ice sheets collapsed in response to climate change during T1 (see Milne, this issue). Other periods in the past also have lessons for millennial-scale climate variability (see Gonzalez and Dupont, this issue).

Paleodata can help constrain the sensitivity of ice volume and sea level change to broader climate change. It can help place limits on future rates of change and it can give a multi-decadal and multi-centennial context to sea level and ice sheet change. The contributions in this edition of *PAGES news* will give recent examples of this work.

Note

For more information on the PALSEA Working Group please visit www.climate.unibe.ch/~siddall/working_group.html

References

Alley, R.B., Clark, P.U., Huybrechts, P. and Joughin, I., 2005: Ice-sheet and sea-level changes, *Science*, **310**: 456-460.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K. and Chappell, J., 1998: Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites, *Earth and Planetary Science Letters*, **163**(1-4): 327-342. DOI:10.1016/S0012-821X(98)00198-8 ().

Gregory, J.M., Lowe, J.A. and Tett, S.B.T., 2006: Simulated global-mean sea-level changes over the last half-millennium, *Journal of Climatology*, **19**(18): 4576-4591.

IPCC, 2007: Summary for Policymakers. In: Solomon, S. et al., (Eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, USA.

PALSEA, 2009: The sea-level conundrum – case studies from paleoarchives, *Journal of Quaternary Science*, in press.

For full references please consult:

www.pages-igbp.org/products/newsletters/ref2009_2.html

Recent Antarctic and Greenland ice-mass fluxes from satellite observations and their significance

Jonathan Bamber

Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, UK; j.bamber@bristol.ac.uk

Understanding contemporary ice sheet behavior is crucial for estimating future trends but the useful satellite observation period of ~20 years is too short. Paleodata, especially from the Holocene, have the potential to help us interpret the contemporary observations.

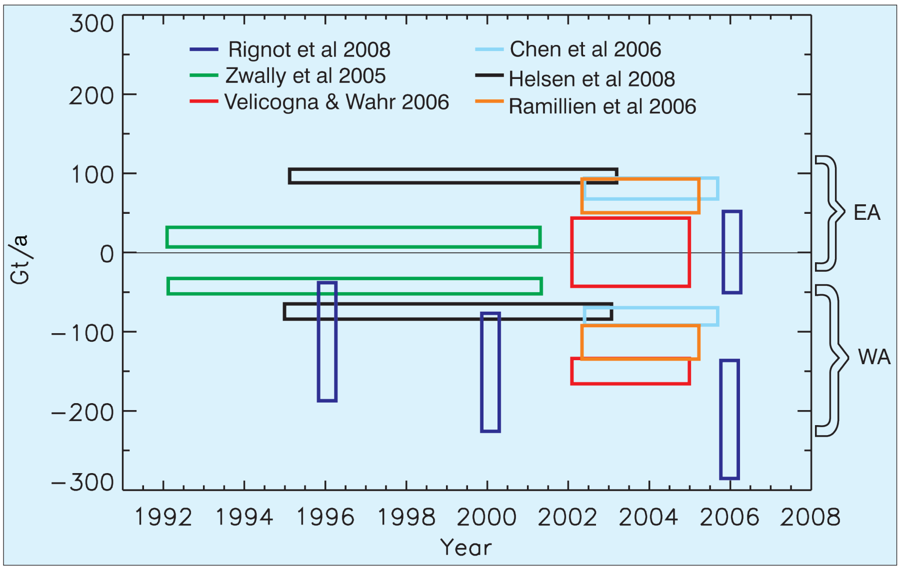

Figure 1: Estimates of the mass balance of the West (WA) and East (EA) Antarctic ice sheets (gigatonnes per year, Gt/a) from a variety of observations and authors. The width of the bars indicates the time period for the estimate and the thickness represents the uncertainty. Zwally et al., (2005) is estimated from satellite radar altimetry. Helsen et al., (2008) is a reassessment of radar altimetry data using a firn compaction model driven by climate model data. (Rignot et al.,, 2008) is from mass budget estimates combining velocity and thickness data with modeled snowfall. Chen et al., 2006, Ramillien et al., 2006, Velicogna and Wahr, 2006 are from gravity measurements from GRACE (Gravity Recovery and Climate Experiment).

Reliable, large-scale observations of the mass trends of the ice sheets do not extend very far back in time. The earliest data set covering the whole of Greenland and 80% of Antarctica began with the launch of ERS-1 in 1991. Since then, other satellites and sensors have provided unique insights into the time-evolving behavior of the ice sheets. Two pressing issues emerge from these observations. The first is the lack of consistency between estimates of the mass balance (Fig. 1), and the second is whether the large and rapid fluctuations in ice dynamics observed are a secular response (i.e., a one-way trend) to external forcing or just part of the "normal" variability in flow that is constantly taking place. Considerable weight and importance has been placed on the apparent increasing mass loss from both Greenland and West Antarctica over the last decade (e.g., Fig. 1). The implication is that this trend is a secular response to external forcing (Hansen, 2007) but the record is too short to confirm this with any certainty. Resolving this issue is crucial, and this is where the paleo record of ice sheet variability, particularly during the Holocene, could, and perhaps must, provide some of the answers.

Since the mid 1990s, our view of ice sheet dynamics has undergone a profound paradigm shift (Bamber et al., 2007). The conventional wisdom was that the response time of ice sheet dynamics was on the order of 10^3-10^4 years. The numerical ice sheet models developed during the 1980s supported this "wisdom" (Huybrechts and de Wolde, 1999). These models operated at relatively course resolution, typically 40 km, with certain simplifications to the physics employed that were considered reasonable at the continental scale. As a consequence, the models were not able to resolve individual ice streams (Fig. 2). During the last decade, with the advent of satellite-based repeat pass synthetic aperture radar interferometry (InSAR), a radically different view has emerged. For example, between 1997 and 2000, the largest outlet glacier (by discharge volume) in Greenland, Jakobshavn