Back to the future: Greenland's contribution to sea-level change

Antony J. Long, *Department of Geography, Durham University, Science Site, South Road, Durham DH1 3LE, UK, a.j.long@durham.ac.uk*

ABSTRACT

The Greenland Ice Sheet is presently making a significant contribution to global sea-level rise. Predictions for the future suggest that this will continue and likely accelerate during the remainder of this century. However, a comprehensive understanding of ongoing mass balance flux has only become possible in the last decade or so, following the development of satellite and other new observational technologies. As a result, it is not clear whether the patterns observed today are typical of the past or not. In this paper, I review predictions for Greenland's contribution to future sea-level rise and then place these estimates in the context of the evidence for change during the twentieth century, the last few millennia, and the Eemian interglacial. There is evidence that the ice sheet responds sensitively to changes in conditions in the adjacent North Atlantic, leading to a hypothesis that annual and decadal fluctuations in Atlantic air and sea surface temperatures shape the ice sheet's contribution to global sea-level change. The recent loss of ice needs also to be seen in the context of an overall increase in ice sheet size and the related advance of the ice sheet margin by tens of kilometers during the past few millennia. I conclude by arguing that in order to better constrain the role of the Greenland Ice Sheet in future sea level, improvements in our understanding of present-day change in the ice sheet must be matched by equal strides in understanding how the ice sheet evolved in the past.

INTRODUCTION

The Greenland Ice Sheet shares center stage with the Antarctic Ice Sheet in current debates about the nature and impacts of global warming. Data suggest that rising northern hemisphere temperatures are causing accelerated ice sheet melting, and according to recently published data collected by the Gravity Recovery and Climate Experiment (GRACE; e.g., Wouters et al., 2008), the Greenland Ice Sheet has contributed ~15%–30% of the global sea-level rise since 2003. Several studies (discussed below) suggest that the Greenland Ice Sheet is capable of contributing >0.5 m of global sea-level rise by the end of this century, with potentially profound social and economic consequences.

But the new data behind such predictions cover only a relatively short time interval, often less than a decade or so, and in the case of GRACE, only since 2002. Short time series such as these need interpreting with caution, since deep boreholes through the ice sheet show that patterns of mass accumulation vary significantly over space and time (e.g., Andersen et al., 2006). Because of this variability, it is important that recent trends in ice sheet mass balance are considered in a longer-term context. Although each successive year of observation generates ever more data, the only way to provide meaningful decadal to century-scale perspectives on Greenland's behavior is to look to the past. We can estimate temperature changes from weather stations for much of the twentieth century (e.g., Chylek et al., 2006) and compute mass balance of the ice sheet from 1958 to 2007 (Rignot et al., 2008) and the surface mass balance back to 1866 (Wake et al., 2009). However, consideration of earlier changes requires examination of proxy records of ice sheet behavior drawn from ice cores, glacial geomorphology, and other paleoclimate archives from Greenland and its adjoining seas.

FUTURE SCENARIOS

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007) predicts that the Greenland Ice Sheet will make a relatively modest contribution to sea-level rise in the next 100 years. Using different low to high emission scenarios, Greenland is estimated to contribute between 0.01 and 0.12 m of global sea-level rise by 2099, out of a total of between 0.18–0.59 m (5%–95% range, based on the interval between 1980 and 1999 and 2090–2099). Thermal expansion of the world's oceans is predicted to be by far the largest contributor to future sea-level rise, accounting for 0.1–0.41 m of sea-level rise by the end of this century. The IPCC recognizes that Greenland's contribution (and that of Antarctica) may be an underestimate, since at the time of the writing of the fourth assessment report, quantitative estimates of the potential dynamic contribution of the ice sheet through accelerated discharge via its outlets could not be made with high confidence. More recent research has sought to quantify what this dynamic contribution could be under high but physically plausible scenarios of ice flux. Using this approach, Pfeffer et al. (2008) conclude that Greenland could contribute between 0.16 and 0.54 m to global sea-level rise by A.D. 2100. When the approach is also applied to Antarctica and other ice caps and glaciers, the combined projection of high, but plausible, sea-level rise by A.D. 2100 lies between 0.78 and 2.08 m, which includes the effects of thermal expansion of the oceans.

How reasonable is it to hypothesize that global sea level might rise several meters within a century and that the Greenland Ice Sheet might contribute >0.5 m to that rise? Some support for such high rates of sea-level rise is forthcoming from a recent study of sea-level changes during the last (Eemian, Marine Isotope Stage 5e) interglacial, ca. 120,000 years ago. At their maximum, global mean temperatures then were comparable to those predicted in the coming century, and sea level

GSA Today, v. 19, no. 6, doi: 10.1130/GSATG40A.1

was several meters higher than present, most likely because much of the Greenland Ice Sheet had melted (Cuffey and Marshall, 2000). Using a Red Sea stable oxygen isotope record from planktonic foraminifera, Rohling et al. (2008) reconstructed average rates of sea-level rise of up to 1.6 m per century during this interglacial. These rates are for periods when sea level was higher than present and are therefore not associated with large glacial-interglacial fluctuations in ice volume. Rohling et al. (2008) did not attribute the source of these large oscillations in sea level, but they note that rates as high as 1.6 m per century would melt the equivalent of the Greenland Ice Sheet in approximately four centuries. There are some important caveats to this work: the height uncertainties are rather large (each sample point has a one-sigma height uncertainty of 6 m), the Red Sea cores used are only partly dated, and the high rates of sea-level variability reported are not fully replicated between the two cores studied. Moreover, equivalent meter-scale fluctuations in sea level are not recorded in the later part of the current interglacial, suggesting a mode of ice sheet dynamic hitherto not seen in the Holocene. Nevertheless, if valid, the research of Rohling et al. (2008) suggests that rapid rates of sea-level rise are possible in the future, especially when sea level is higher than present, although an implication of the Pfeffer et al. (2008) study is that, on its own, Greenland would only be able to contribute about a third of the proposed 1.6 m rise per century, and probably less given the ice sheet's reduced size at this time.

So, it is plausible that the Greenland Ice Sheet might contribute >0.5 m of global sea-level rise in the next century, and some believe that such high rates of global sea-level rise have occurred in the past. Such a rise would require a sustained high flux of ice over the entire coming century. However, there is considerable evidence from the past to show that the mass balance of the Greenland Ice Sheet fluctuates on a decadal basis, experiencing phases of positive and negative mass balance that change broadly, in tune with variations in air and sea surface temperatures over Greenland and the neighboring North Atlantic.

GREENLAND'S CONTRIBUTION TO TWENTIETH-CENTURY SEA LEVEL

Tide gauge and satellite observations show that global sea level rose during the twentieth century, but the rate of rise was not constant. Thus, Cazenave et al. (2008) estimate that global sea-level rise between January 1993 and February 2008 was 3.1 ± 0.1 mm/a (Fig. 1), which compares with an average rate during the past 50 years of ~1.7 mm/a (Church and White, 2006; Holgate, 2007). Estimates obtained from remotely sensed data of Greenland's changing mass during the past decade vary widely, but all suggest the ice sheet today is making a positive contribution to global sea-level rise. Initial observations suggested that peripheral thinning of the ice sheet was offset by thickening above 2000 m (Krabill et al., 2000; Thomas et al., 2006) such that the overall sea-level contribution was negligible (Zwally et al., 2005). However, more recent observations by the GRACE satellites show significant mass loss from the higher parts of the ice sheet as well, due to longer and more intense melt seasons, especially in 2007 (Wouters et al., 2008) (Fig. 2).

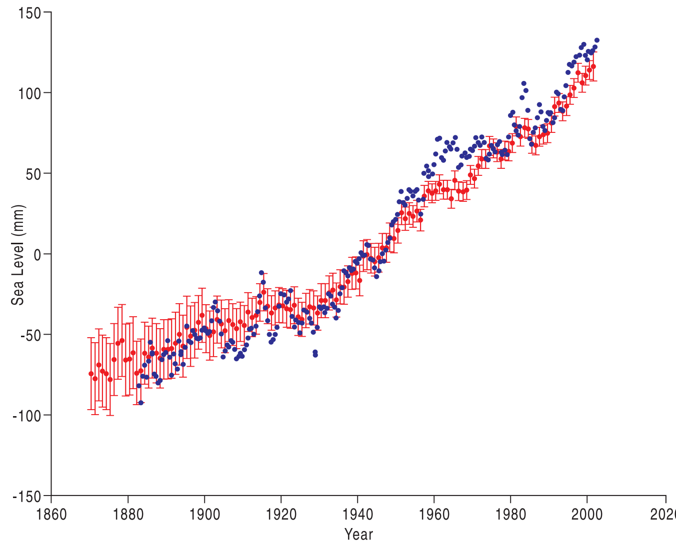

Figure 1. Estimates of twentieth-century global sea-level change (Cazenave et al., 2008). Red dots are from Church and White (2006) and blue dots are from Jevrejeva et al. (2006).

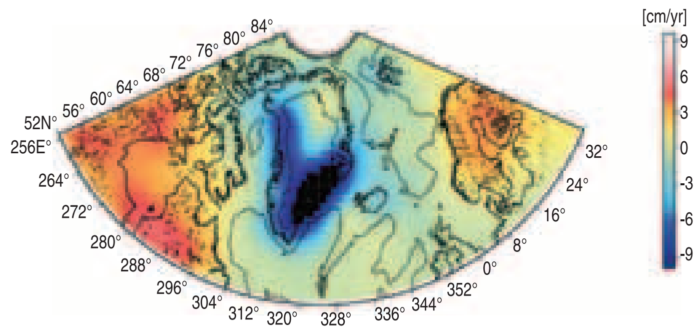

Figure 2. Changes in equivalent water height over Greenland between February 2003 and January 2008 as observed by the Gravity Recovery and Climate Experiment (GRACE) (Wouters et al., 2008).

The cause of this mass loss seems clear: rising temperatures are causing increased melting. For example, summer temperatures have risen by an average of 1.7 °C over the southern part of Greenland between 1991 and 2006, and this has lengthened the melt season (Hanna et al., 2008). Many outlet glaciers here and elsewhere in Greenland have accelerated their speed (Rignot and Kanagaratnam, 2006; Luckman et al., 2006; Howat et al., 2008), and many coastal glaciers have also thinned significantly (Thomas et al., 2006). Water generated by greater surface melt may percolate to the bed of the ice sheet and reduce basal friction, causing the rate of flow of the glaciers to speed up (Zwally et al., 2002), although the significance of this process is debated (Joughin et al., 2008). Moreover, warm ocean currents penetrating fjords are also associated with increased melting of glaciers and ice streams with marine termini (Holland et al., 2008; Hanna et al., 2009). But the broader implications of some of these recent changes for the long-term decadal to century-scale ice sheet stability are uncertain. In the past few years, several of the retreating glaciers have slowed or even started to re-advance (Howat et al., 2007). Moreover, Nick et al. (2009) use a numerical model to demonstrate that tidewater outlet glaciers are very sensitive to changes in their terminus boundary conditions and adjust quickly and dynamically to short-term climate fluctuations. They warn that recent dynamic instabilities in the Helheim Glacier in southeast Greenland, and potentially elsewhere, do not provide a reliable basis for long-term prediction of ice sheet mass balance change.

The recent loss of mass from Greenland means it is now making an increasingly positive contribution to global sea-level rise. Estimates from GRACE since 2002 vary between 100 and 270 Gt/a, which is equivalent to a sea-level rise of ~0.4–0.7 mm/a (Velicogna and Wahr, 2006; Ramillien et al., 2006; Chen et al., 2006; Luthcke et al., 2006; Wouters et al., 2008). The variability in these estimates reflects differences in the time period of observation, data sources, and methods used in data analysis, as well as real spatial and temporal variations in ice sheet volume. Cazenave et al. (2008) concluded that since 2003 the rate of global sea-level rise decreased from 3.1 ± 0.1 to 2.5 ± 0.5 mm/a largely due to reduced thermal expansion of the oceans. Recent GRACE estimates show that Greenland is presently contributing between ~15%–30% of global sea-level rise, well above the IPCC estimates.

A longer-term twentieth-century perspective is provided by modeling experiments that accurately account for vertical changes in both the sea surface and the sea floor when ice sheets gain or lose mass. Thus, Mitrovica et al. (2001) analyzed spatial trends in rates of tide-gauge measured sea level for 23 selected sites. They observed that rates of twentieth-century sea-level rise in European sites were lower than the global average and concluded that this sea-level "fingerprint" is compatible with a Greenland contribution to global sea level of ~0.6 mm/a during the twentieth century. This estimate is within the range cited from the GRACE studies of recent Greenland contribution to global sea-level rise (~0.4–0.7 mm/a). Resolving the ongoing spatial pattern of sea-level fingerprints is likely to be complex, not least due to non-uniform variations in thermal expansion. Nevertheless, this important analysis suggests a persistent and significant positive Greenland contribution to global sea level during the twentieth century.

Greenland and the North Atlantic

The Greenland Ice Sheet owes much of its existence to the large moisture source provided by the adjacent North Atlantic; although the ice sheet responds to variations in a variety of forcing factors, including volcanic activity and solar output (e.g., Hanna et al., 2005), it is no surprise to find that it is also sensitive to changes in atmospheric and oceanographic conditions in the North Atlantic region. This sensitivity is illustrated by considering how the climate over Greenland responds to fluctuations in the North Atlantic Oscillation (NAO) and the Atlantic Multi-decadal Oscillation (AMO). The mechanisms that cause fluctuations in these indices are not certain, although it seems probable that they respond at least in part to the non-linear dynamics of the extratropical atmosphere and variations in the strength of the thermohaline circulation (Hurrell et al., 2001; Sutton and Hodson, 2005). Neither is presently predictable to any significant degree and, for example, a return to cooler conditions over Greenland in future decades might be expected if their previous pattern of variability continues into the future.

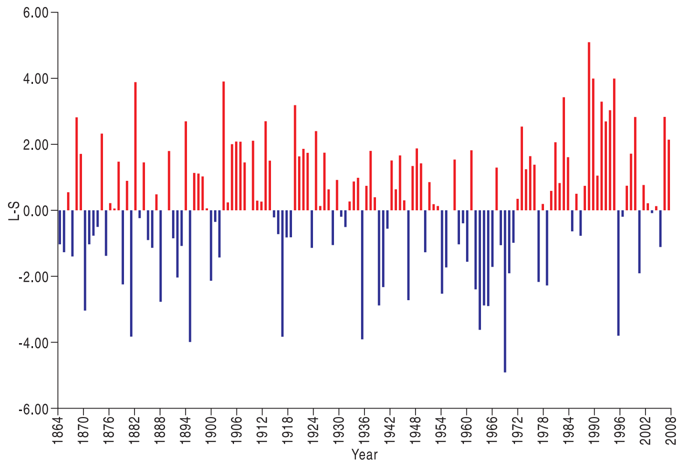

Figure 3. Winter (Dec.–Mar.) index of the North Atlantic Oscillation (NAO) based on the difference of normalized sea-level pressure between Lisbon (L), Portugal, and Stykkisholmur/Reykjavik (S), Iceland, since 1864. Positive values of the index indicate stronger-than-average westerlies over the middle latitudes (http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

The NAO describes a redistribution of atmospheric mass between the Arctic and the subtropical Atlantic. Variations in NAO phases generate large changes in surface air temperature, winds, storminess, and precipitation over the Atlantic and also influence the oceans by causing changes in heat content, gyre circulations, salinity, high-latitude deep-water formation, and sea ice cover (Hurrell et al., 2001). There is no agreed method for defining the NAO, although one measure is provided by the varying sea-level pressure between the Icelandic low and the Azores subtropical high pressure system (Fig. 3). The NAO is positive when the Icelandic low is deep, causing enhanced westerly air flow across the North Atlantic, with cold and dry conditions over Greenland. A shift to a weaker or negative NAO (associated with a weaker Icelandic low) brings warmer conditions and higher precipitation over Greenland. Higher air temperatures over Greenland since the early 1990s (Hanna et al., 2008), as well as the penetration of warmer ocean currents into the fjords of south Greenland since the mid-1990s (Holland et al., 2008), are compatible with the gradual shift from a positive to a more negative NAO since the mid 1980s (Box, 2002; Hanna et al., 2008) (Fig. 3).

Further evidence of the close link between conditions in the North Atlantic and across the Greenland Ice Sheet is provided by the AMO. The AMO describes a 65–75 year variation (0.4 °C range) in North Atlantic sea surface temperatures (SST). Expressed as deviations from the 1961–1990 mean, the AMO is characterized by warm (1930–1960) and cool (1905–1925 and 1970–1990) SST phases. The AMO returned to more positive values again in the 1990s (Fig. 4A). There is widespread evidence that changes in the AMO are related to multidecadal variations in a range of climate records, including Atlantic hurricanes and North American and European summer climate (e.g., Knight et al., 2006).

Temperature records from coastal stations in Greenland show that the recent increase in temperatures is not unprecedented in the last century and that an earlier episode of warmer than average temperatures is likely linked to changes in the

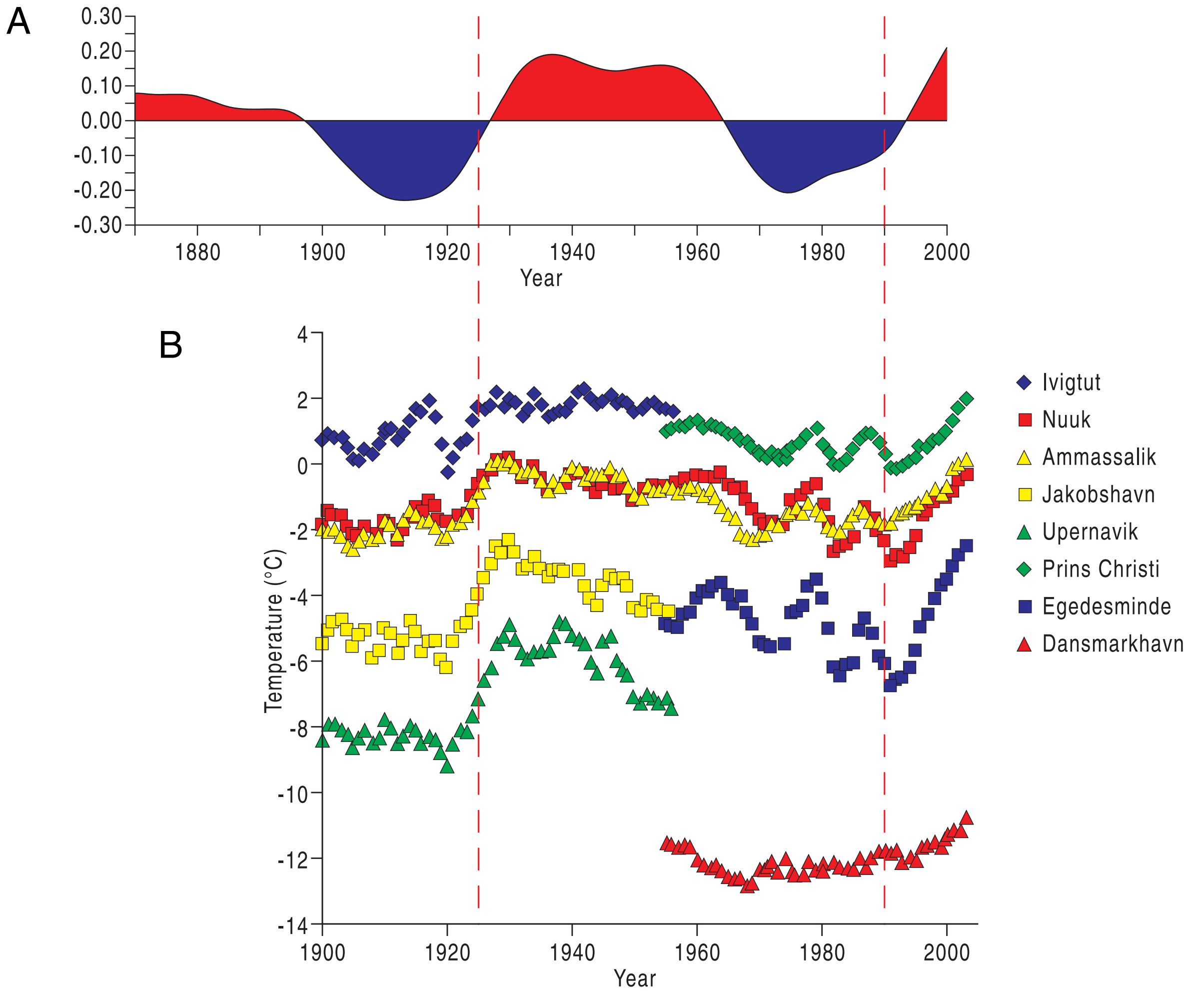

Figure 4. (A) Index of the Atlantic Multi-decadal Oscillation, 1871–2003. The index was calculated by averaging annual mean sea surface temperature observations over the region 0°N to 60°N, 75°W to 7.5°W. The units on the vertical axis are degrees Celsius (Sutton and Hodson, 2005). (B) Annual average temperatures from eight weather stations in Greenland showing similar warming in the periods 1920–1930 and 1995–2005 (Chylek et al., 2006).

AMO. Thus, Chylek et al. (2006) conclude that the rate of warming in Greenland between 1930 and 1940 was ~50% higher than that observed between 1995 and 2005 (Fig. 4B). Both warm phases broadly coincide with periods when the AMO shifted from a cooler to a warmer phase. These climate fluctuations almost certainly impacted the mass balance of the ice sheet. A recently published mass balance history for the ice sheet extending back to 1958 reconstructs mass deficit during the warm 1960s (110 ± 70 Gt/a), near balance in the cool 1970s–1980s (30 ± 50 Gt/a), and accelerated loss since the 1990s (up to 267 ± 38 Gt/a in 2007) (Rignot et al., 2008). These estimates are in broad agreement with reconstructed trends in surface mass balance by Hanna et al. (2005). Wake et al. (2009) identify a distinct change from positive to negative surface mass balance anomalies during the pronounced warming that began in the 1920s and continued until ca. 1960. They conclude that the surface mass balance changes between 1995 and 2005 are not exceptional within the past 140 years.

Is there any proven link between these ice mass fluctuations in Greenland, temperatures, and changes in the rate of twentieth-century global sea level? Although the overall trend in twentieth-century sea level was upward, there have been periods of faster and slower rates of change. The two decades showing the fastest increase in global sea level are centered on 1980 (+5.31 mm/a) and 1939 (+4.68 mm/a), while the lowest rates of change are centered on 1964 (–1.49 mm/a) and 1987 (–1.38 mm/a) (Holgate, 2007). Woodworth et al. (2008) reviewed possible links between periods of accelerated and reduced rates of global sea-level rise and variations in the NAO and AMO and a range of other climate indicators that include the Pacific Decadal Oscillation, Arctic Oscillation, and the Southern Oscillation Index. They concluded that many of these indices change in phase with the major variations in the rate of global sea-level rise. In terms of Greenland's contribution to these sea-level fluctuations, the warmth of the 1980s and the cool period of the 1960s coincide with changes in ice sheet mass balance identified by Rignot et al. (2008). Moreover, the change modeled by Wake et al. (2009) in the 1920s coincides with the acceleration in global sea level noted at this time by Holgate (2007) and Woodworth et al. (2008), although the Wake et al. (2009) analysis did not include potential variations in ice sheet dynamic contributions and estimates for outlet glacier discharge in their study. Given these findings, it is reasonable to propose that decadal variations in the mass balance of the Greenland Ice Sheet were, in part at least, responsible for variations in the rate of global sea-level rise during the twentieth century.

GREENLAND'S CONTRIBUTION TO SEA LEVEL DURING THE LAST FEW MILLENNIA

Neoglacial Ice Sheet Growth

The "neoglacial" extends from ~4000 years ago to the end of the Little Ice Age and is characterized by a shift to cooler conditions. According to temperature profiles from the Dye 3 and GRIP ice cores, this was equivalent to a 2 °C fall in average air temperatures over the center of the ice sheet between 4000 and 2000 years ago, with further cool periods ca. A.D. 1500 and A.D. 1750 (Dahl-Jensen et al., 1998). There is geomorphological and sea-level evidence from Greenland to suggest that the ice sheet margin advanced over the duration of the neoglacial (Kelly, 1980; Weidick, 1993; van Tatenhove et al., 1996; Long et al., 2009). This evidence includes reworked organic material ripped up from former tundra surfaces by advancing ice, reworked late Holocene marine faunas in recent moraines adjacent to tidewater glaciers, and a rise in relative sea level in west and south Greenland driven, in part at least, by renewed ice loading during the late Holocene (Kelly, 1980).

Reconstructing the magnitude and timing of the neoglacial advance is difficult because a growing ice sheet destroys former ice limits. Ice sheet models provide the best means of estimating ice volume changes, especially when they are constrained by sea level and other geomorphological evidence. Current models suggest that despite the 50–100 km advance of the ice sheet margin, especially in west Greenland where it was most pronounced, the neoglacial regrowth of the ice sheet caused a relatively small draw-down of global sea level, amounting to <0.2 m (Tarasov and Peltier, 2002; Fleming and Lambeck, 2004; Simpson et al., 2009). This is equivalent to a rate of sea-level fall of ~0.05 mm/a when averaged over the past 4000 years.

In reality, it is likely that regrowth of the ice sheet and its associated impact on global sea-level varied over time. The most pronounced periods of neoglacial cooling recorded in the ice cores occurred between 4000 and 2000 B.P., A.D. 1000–1500, and ca. A.D. 1850 (Dahl-Jensen et al., 1998). If we assume that these cooler intervals coincided with ice sheet expansion, then these are the periods that Greenland is most likely to have slowed global sea-level rise. Conversely, warmer conditions identified by Dahl-Jensen et al. (1998) occur between 0 and 1000 A.D., A.D. 1500–1750, and after A.D. 1850, and it is reasonable to hypothesize that these intervals were associated with positive global sea level contributions. Beyond Greenland, there is no evidence for coherent variations in the rate of sea-level change during the late Holocene that can be unambiguously attributed to variations in the neoglacial volume of the Greenland Ice Sheet, although an acceleration during the past 100–150 years seems widespread and may have a Greenland origin (e.g., Gehrels et al., 2008).

The record from the last few thousand years shows that the Greenland Ice Sheet has experienced a significant increase in mass during the cooler conditions of the "neoglacial." All around the margins of the present ice sheet are fresh moraines that mark the maximum position of this advance, reached at the end of the Little Ice Age (the late nineteenth or early twentieth century). Most of these lie within a few kilometers of the present ice sheet margin, showing that the ice sheet was more extensive in the recent past. Although retreat is obvious in many areas, in west Greenland there remains a considerable distance between the present ice margin and its position at the start of the neoglacial, when model experiments suggest that the margin lay many tens of kilometers inland of its present position (e.g., Simpson et al., 2009).

CONCLUSIONS

Predictions suggest that the Greenland Ice Sheet could contribute >0.5 m of global sea-level rise by the end of this century, and one sensitivity study predicts that rates of mass loss would match those last seen as far back as ~10,000 years ago, at the time of fastest ice sheet retreat (Pfeffer et al., 2008). Satellite and field observations show that the evolving mass of the Greenland Ice Sheet is making an increasingly positive contribution to global sea-level rise and, although estimates vary, GRACE data indicate this contribution is between 0.4 and 0.7 mm/a, equal to ~15%–30% of the total global rise in sea level measured since 2003. The present contribution is considerably larger than predicted by the Fourth IPCC Assessment Report but is less than some high-end estimates of sea-level rise from Greenland in the next century (e.g., Pfeffer et al., 2008) and the range of high rates of sea-level rise reconstructed from the last interglacial (Rohling et al., 2008).

The improved spatial and temporal resolution of recent geodetic methods means that we are gaining new and unprecedented insights into the dynamics of the ice sheet, its glaciers, and ice streams. These observations are rapidly changing our understanding of how Greenland responds to climate change. There is, for example, growing evidence that the surface mass balance and glacier dynamics in Greenland are related to changes in air and ocean temperatures that vary in phase with changing conditions in the adjacent North Atlantic. Two periods of rapid atmospheric warming in the twentieth century, one in the 1980s and the other in the 1920s, coincide with phase shifts in the AMO and likely saw Greenland making a positive contribution to accelerations in the rate of global sea-level rise recorded by tide gauge records. But advances in current-change monitoring must be matched by the development of new understanding regarding the past behavior of the ice sheet. We still know very little regarding the mass balance history of the ice sheet during the past few centuries, despite the large climate changes that existing records suggest have occurred. Future research must bridge the gap between geological reconstructions and recent direct observations if we are to establish firm decadal and century-scale trends in ice sheet mass balance and hence determine whether the variations we observe today are within or beyond normal ice sheet variability. Only then will we reduce the considerable uncertainty that presently exists regarding the contribution of the Greenland Ice Sheet to past and future sea-level change.

ACKNOWLEDGMENTS

I thank my collaborators on this project for their insightful discussions, especially Glenn Milne, Sarah Woodroffe, and Roland Gehrels. I also thank Jerry Mitrovica, an anonymous referee, and *GSA Today* science editor Stephen Johnston for their helpful comments on this paper during review. This paper is a contribution to International Geological Correlation Programme (IGCP) Project 495 "Quaternary Land-Ocean Interactions: Driving Mechanisms and Coastal Responses" and the International Union for Quaternary Research (INQUA) Commission on Coastal and Marine Processes. This research draws on work conducted under Natural Environment Research Council (NERC) Grant NE/C519311/1.

REFERENCES CITED

Andersen, K.K., Ditlevsen, P.D., Rasmussen, S.O., Clausen, H.B., Vinther, B.M., Johnsen, S.J., and Steffensen, J.P., 2006, Retrieving a common accumulation record from Greenland ice cores for the past 1800 years: Journal of Geophysical Research, v. 111, doi: 10.1029/2005JD006765.

Box, J.E., 2002, Survey of Greenland instrumental temperature records: 1873–2001: International Journal of Climatology, v. 22, p. 1829–1847, doi: 10.1002/joc.852.

Cazenave, A., Lombard, A., and Llovel, W., 2008, Present-day sea-level rise: A synthesis: Comptes Rendus Geoscience, v. 340, p. 761–770, doi: 10.1016/j.crte.2008.07.008.

Chen, J.L., Wilson, C.R., and Tapley, B.D., 2006, Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet: Science, v. 313, p. 1958–1960, doi: 10.1126/science.1129007.

Church, J.A., and White, N.J., 2006, A 20th century acceleration in global sea-level rise: Geophysical Research Letters, v. 33, doi: 10.1029/2005GL024826

Chylek, P., Dubey, M.K., and Lesins, G., 2006, Greenland warming of 1920–1930 and 1995–2005: Geophysical Research Letters, v. 33, doi: 10.1029/2006GL026510.

Cuffey, K.M., and Marshall, S.J., 2000, Substantial contribution to sea-level rise during the last interglacial from the Greenland Ice Sheet: Nature, v. 404, p. 591–594, doi: 10.1038/35007053.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W., and Balling, N., 1998, Past temperatures directly from the Greenland Ice Sheet: Science, v. 282, p. 268–271, doi: 10.1126/science.282.5387.268.

Fleming, K., and Lambeck, K., 2004, Constraints on the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models: Quaternary Science Reviews, v. 23, p. 1053–1077, doi: 10.1016/j.quascirev.2003.11.001.

Gehrels, W.R., Hayward, B.W., Newnham, R.M., and Southall, K.E., 2008, A 20th century sea-level acceleration in New Zealand: Geophysical Research Letters, v. 35, doi: 10.1029/2007GL032632.

Hanna, E., Huybrechts, P., Janssens, I., Cappelen, J., Steffen, K., and Stephens, A., 2005, Runoff and mass balance of the Greenland Ice Sheet: 1958–2003: Journal of Geophysical Research, v. 110, doi: 10.1029/2004JD005641.

Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-Fynn, T., Wise, S., and Griffiths, M., 2008, Increased runoff from melt from the Greenland Ice Sheet: A response to global warming: Journal of Climate, v. 21, p. 331–341, doi: 10.1175/2007JCLI1964.1.

Hanna, E., Cappelen, J., Fettweis, X., Huybrechts, P., Luckman, A., and Ribergaard, M.H., 2009, Hydrologic response of the Greenland Ice Sheet: The role of oceanographic warming: Hydrological Processes, doi: 10.1002/hyp.7090 (in press).

Holgate, S., 2007, On the decadal rates of sea level change during the twentieth century: Geophysical Research Letters, v. 34, doi: 10.1029/2006GL028492.

Holland, D.M., Thomas, R.H., De Young, B., Ribergaard, M.H., and Lyberth, B., 2008, Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters: Nature Geoscience, v. 1, p. 659–664, doi: 10.1038/ngeo316.

Howat, I.M., Joughin, I., and Scambos, T.A., 2007, Rapid changes in ice discharge from Greenland outlet glaciers: Science, v. 315, p. 1559–1561, doi: 10.1126/science.1138478.

Howat, I.M., Joughin, I., Fahnestock, M., Smith, B.E., and Scambos, T.A., 2008, Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000-06: Ice dynamics and coupling to climate: Journal of Glaciology, v. 54, p. 646–660, doi: 10.3189/002214308786570908.

Hurrell, J.W., Hoerling, M.P., and Folland, C.K., 2001, Climatic variability over the North Atlantic: Meteorology at the Millennium: 150th Aniversary of the Royal Meteorological Society, London, Academic Press, p. 143–151.

IPCC, 2007, 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, UK, Cambridge University Press, 996 p.

Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S., 2006, Nonlinear trends and multiyear cycles in sea level records: Journal of Geophysical Research, doi: 10.1029/2005JC003229.

Joughin, I., Das, S.B., King, M.A., Smith, B.E., Howat, M., and Mooni, T., 2008, Seasonal speedup along the western flank of the Greenland Ice Sheet: Science, v. 320, p. 781–783.

Kelly, M., 1980, The status of the Neoglacial in Western Greenland: Rapport Grønlands Geologiske Undersøgelse, v. 96, 24 p.

Knight, J.R., Folland, C.K., and Scaife, A.A., 2006, Climate impacts of the Atlantic Multidecadal Oscillation: Geophysical Research Letters, v. 33, doi: 10.1029/2006GL026242.

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, C., and Yungel, Y., 2000, Greenland Ice Sheet: High-elevation balance and peripheral thinning: Science, v. 289, p. 428–430.

Long, A.J., Woodroffe, S.A., Dawson, S., Roberts, D.H., and Bryant, C.L., 2009, Late Holocene relative sea level rise and the Neoglacial history of the Greenland ice sheet: Journal of Quaternary Science, doi: 10.1002/jqs.1235.

Luckman, A., Murray, T., de Lange, R., and Hanna, E., 2006, Rapid and synchronous ice-dynamic changes in East Greenland: Geophysical Research Letters, v. 33, L03503, doi: 10.1029/2005GL025428.

Luthcke, S.B., Zwally, H.J., Abdalati, W., Rowlands, D.D., Ray, R.D., Nerem, R.S., Lemoine, F.G., McCarthy, J.J., and Chinn, D.S., 2006, Recent Greenland ice mass loss by drainage system from satellite gravity observations: Science, v. 314, p. 1286–1289, doi: 10.1126/science.1130776.

Mitrovica, J.X., Tamisiea, M., Davis, J.L., and Milne, G.A., 2001, Recent mass balance of polar ice sheets inferred from patterns of global sea-level change: Nature, v. 409, p. 1026–1029, doi: 10.1038/35059054.

Nick, F.M., Vieli, A., Howat, I.M., and Joughin, I., 2009, Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus: Nature Geoscience, v. 2, p. 110–114, doi: 10.1038/ngeo394.

Pfeffer, W.T., Harper, J.T., and O'Neel, S., 2008, Kinematic constraints on glacier contributions to 21st-century sea-level rise: Science, v. 321, p. 1340–1343, doi: 10.1126/science.1159099.

Ramillien, G., Lombard, A., Cazenave, A., Ivins, E.R., Llubes, M., Lemy, F., and Biancale, R., 2006, Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE: Global and Planetary Change, v. 53, p. 198–208, doi: 10.1016/j.gloplacha.2006.06.003.

Rignot, E., and Kanagaratnam, P., 2006, Changes in the velocity structure of the Greenland ice sheet: Science, v. 311, p. 986–990.

Rignot, E., Box, J.E., Burgess, E., and Hanna, E., 2008, Mass balance of the Greenland ice sheet from 1958 to 2007: Geophysical Research Letters, v. 35, doi: 10.1029/2008GL035417.

Rohling, E.R., Grant, K., Hemleben, C.H., Siddall, M., Hoogakker, B.A.A., Bolshaw, M., and Kucera, M., 2008, High rates of sea-level rise during the last interglacial period: Nature Geoscience, v. 1, p. 38–42, doi: 10.1038/ngeo.2007.28.

Simpson, M.J.R., Milne, G.A., Huybrechts, P., and Long, A.J., 2009, Calibrating a glaciological model of the Greenland Ice Sheet from the last glacial maximum to present-day using field observations of relative sea level and ice extent: Quaternary Science Reviews (in press).

Sutton, R.T., and Hodson, D.L.R., 2005, Atlantic Ocean forcing of Northern American and European summer climate: Science, v. 309, p. 115–118, doi: 10.1126/science.1109496.

Tarasov, L., and Peltier, W.R., 2002, Greenland glacial history and local geodynamic consequences: Geophysical Journal International, v. 150, p. 198–229, doi: 10.1046/j.1365-246X.2002.01702.x.

Thomas, R., Frederick, E., Krabill, W., Manizade, S., and Martin, C., 2006, Progressive increase in ice loss from Greenland: Geophysical Research Letters, v. 33, L10503, doi: 10.1029/2006gl026075.

van Tatenhove, F.G.M., van der Meer, J.J.M., and Koster, E.A., 1996, Implications for deglaciation chronology from new AMS age determinations in central west Greenland: Quaternary Research, v. 45, p. 245–253, doi: 10.1006/qres.1996.0025.

Velicogna, I., and Wahr, J., 2006, Acceleration of Greenland ice mass loss in spring 2004: Nature, v. 443, p. 329–331, doi: 10.1038/nature05168.

Wake, L.M., Huybrechts, P., Box, J.E., Hanna, E., Janssens, I., and Milne, G.A., 2009, Surface mass-balance changes of the Greenland Ice Sheet since 1866: Annals of Glaciology, v. 50, p. 178–184, doi: 10.3189/172756409787769636.

Weidick, A., 1993, Neoglacial change of ice cover and the related response of the Earth's crust in West Greenland: Rapport Grønlands Geologiske Undersøgelse, v. 159, p. 121–126.

Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A., and Gehrels, W.R., 2008, Evidence for the accelerations of sea level on multi-decade and century timescales: International Journal of Climatology, doi: 10.1002/joc.1771.

Wouters, B., Chambers, D., and Schrama, E.J.O., 2008, GRACE observes small-scale mass loss in Greenland: Geophysical Research Letters, v. 35, doi: 10.1029/2008GL034816.

Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002, Surface melt-induced acceleration of Greenland ice-sheet flow: Science, v. 297, p. 218–222, doi: 10.1126/science.1072708.

Zwally, H.J., Giovenetto, M.B., Li, J., Corneio, H.G., Beckley, M.A., Brenner, A.C., Saba, J.L., and Yi, D.H., 2005, Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002: Journal of Glaciology, v. 51, p. 509–527, doi: 10.3189/172756505781829007.

Manuscript received 16 January 2009; accepted 24 March 2009.