

The sea-level conundrum: case studies from palaeo-archives

PALSEA*[†] (PALeo SEA level working group)

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ABSTRACT: Uncertainties in sea-level projections for the 21st century have focused ice sheet modelling efforts to include the processes that are thought to be contributing to the recently observed rapid changes at ice sheet margins. This effort is still in its infancy, however, leaving us unable to make reliable predictions of ice sheet responses to a warming climate if such glacier accelerations were to increase in size and frequency. The geological record, however, has long identified examples of nonlinear ice sheet response to climate forcing (Shackleton NJ, Opdyke ND. 1973. Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28–239, late Pliocene to latest Pleistocene. *Geological Society of America Memoirs* **145**: 449–464; Fairbanks RG. 1989. A 17,000 year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature* **342**: 637–642; Bard E, Hamelin B, Arnold M, Montaggioni L, Cabioch G, Faure G, Rougerie F. 1996. Sea level record from Tahiti corals and the timing of deglacial meltwater discharge. *Nature* **382**: 241–244), thus suggesting an alternative strategy for constraining the rate and magnitude of sea-level change that we might expect by the end of this century. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: sea level; climate change; ice sheets.



Background

The eustatic sea-level (ESL) rise predicted for the 21st century represents one of the greatest potential threats from climate change, yet its magnitude remains a subject of considerable debate (Oppenheimer *et al.*, 2007, 2008; Solomon *et al.*, 2008), with worst-case scenarios varying between 0.59 m (IPCC; Meehl *et al.*, 2007) and 1.4 m (Rahmstorf, 2007a). In general, the basis for this debate revolves around the uncertainties in the dynamical behaviour of ice sheets (such as loss of buttressing through ice shelf break-up or enhanced ice flow through water lubrication of the ice sheet base), which may lead to a nonlinear

sea-level response to climate change (Alley *et al.*, 2005). IPCC Fourth Assessment Report (AR4) projections of 21st-century sea-level rise included an estimate of the dynamical response simulated by existing continental ice sheet models, giving them a value of –0.01 to 0.17 m over the next century. However, this did not include rapid dynamical responses of ice sheets to climate change such as the acceleration of ice streams (Meehl *et al.*, 2007). This is problematic because such rapid changes have been observed on Greenland's Jakobshavn Isbrae glacier (e.g. Joughin *et al.*, 2004). There are also substantial uncertainties in how the surface mass balance of the Greenland ice sheet will respond in the future (Bougamont *et al.*, 2007). Rahmstorf (2007a) subsequently attempted to predict sea-level rise over the 21st century using a simple response model which assumes an increase in the rate of sea-level response to global warming that is proportionate to the post-industrial global temperature perturbation. However, this attempt was controversial because of the relatively short length of the period used to scale the model (Holgate *et al.*, 2007) and the assumed causality of a sea-level response to temperature (Schmith *et al.*, 2007; Rahmstorf, 2007b). Horton *et al.* (2008) used an alternative approach by examining the response from a suite of general circulation models (GCMs), but again dynamical responses were not included.

In August 2008, PAGES, IMAGES and the University of Bern cosponsored a workshop entitled 'Empirical constraints on future sea-level rise' to address the possibility of using palaeo sea-level data to place limits on projections of future sea-level rise. Several issues were considered, including whether there

*Correspondence to: M. Siddall, Department of Earth Science, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK.
E-mail: mark.siddall@bristol.ac.uk

[†]Ayako Abe-Ouchi (University of Tokyo), Morten Andersen (University of Bristol), Fabrizio Antonioli (ENEA), Jonathon Bamber (University of Bristol), Edouard Bard (CEREGE, CNRS), Jorie Clark (University of Ulster), Peter Clark (Oregon State University), Pierre Deschamps (CEREGE, CNRS), Andrea Dutton (ANU), Mary Elliot (University of Edinburgh), Christina Gallup (University of Minnesota), Natalya Gomez (University of Toronto), Jonathan Gregory (University of Reading), Peter Huybers (Harvard University), Kenji Kawamura (University of Tohoku), Meredith Kelly (LDEO), Kurt Lambeck (ANU), Tom Lowell (University of Cincinnati), Jerry Mitrovica (University of Toronto), Bette Otto-Bliesner (NCAR), David Richards (University of Bristol), Mark Siddall (LDEO), Jenny Stanford (NOC), Claudine Stirling (University of Otago), Thomas Stocker (University of Bern), Alex Thomas (University of Oxford), Bill Thompson (WHOI), Torbjörn Törnqvist (Tulane University), Natalia Vazquez Riveiros (LSCE), Claire Waelbroeck (LSCE), Yusuke Yokoyama (University of Tokyo), Shiyong Yu (Tulane University).

are typical modes of ice sheet response to climatic perturbations and constraining the magnitude of sea-level response to temperature perturbations in the past, particularly during previous interglacial periods. Here we discuss and enlarge upon the issues discussed at this workshop. These issues fall into two general categories: (1) dynamic responses of relative sea-level (RSL) to temperature change (i.e. typical response times which define the lag of ice volume to a temperature perturbation); and (2) the eustatic sea level (ESL) associated with quasi-steady states (interglacial high stands), which followed several thousand years after a given perturbation to the climate. These two categories cannot be considered in isolation because establishing what represents a 'quasi-steady state' for a given interglacial period depends on the changes which precede the interglacial period. Here we summarise several approaches discussed at the workshop that elucidate possible directions to help address these questions.

Palaeo-sea-level records

Extracting the history of past ESL changes from sea-level records requires accounting for the redistribution of mass due to growth and decay of ice sheets that results in isostatic compensation of the underlying solid Earth. This process is referred to as glacial isostatic adjustment (GIA). The redistribution of mass causes vertical (glacio- and hydro-isostatic) motions that may be recorded along any given coastline where the global sea level serves as a datum. Because changes in ice mass will also cause changes in regional (due to gravitational and rotational feedbacks) and global (due to volume) sea level (Lambeck *et al.*, 2002; Milne *et al.*, 2002), the changes in sea level at a particular coastline record the difference between vertical motions of the land and sea, commonly referred to as relative sea-level (RSL) changes. Such isostatic effects are a function of the distance from the large ice sheets. If we assume a steady reduction of the rate of ESL rise approaching an interglacial high stand, three broad classes of RSL records exist due to the viscoelastic response of the crust (Clark *et al.*, 1978; Fleming *et al.*, 1998; Mitrovica and Milne, 2002) (Fig. 1): (1) near-field records (large imprint of glacio-isostasy, RSL may be antiphased with ESL); (2) intermediate-field records (reduced imprint of

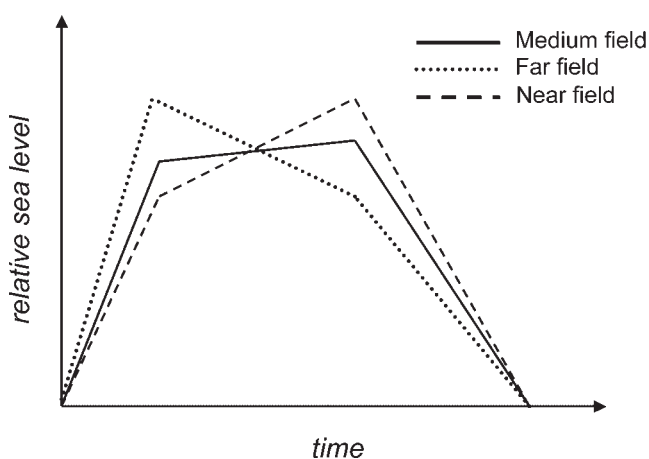


Figure 1 An illustrative sketch of relative sea-level change during an interglacial period. Far-field sites respond early and 'overshoot' eustatic sea level at the start of the interglacial; near-field sites respond late and 'overshoot' eustatic sea level at the end of the interglacial; medium-field sites are closest to eustatic sea level

glacio-isostasy with some phase shifts of the onset of interglacial RSL compared to ESL); and (3) far-field records (primarily hydro-isostasy, interglacial sea level reaches an early peak compared to ESL and then falls gradually). These characteristic features of palaeo-RSL data are used to inform solid-Earth models of GIA which are in turn used to correct records of recent sea-level rise from tide gauge data (Church and White, 2006) as well as the satellite altimetry and gravity data used to infer changes in ice mass (Velicogna and Wahr, 2006; Barletta *et al.*, 2008). Therefore RSL data are a key component in contemporary sea-level rise studies, a point that emphasises the important role of palaeo-sea-level studies in understanding the ongoing rise in ESL today. Because of the spatial patterns found when comparing RSL data at multiple sites due to the elastic response of the crust to ice sheet collapse, RSL data also provide important constraints on the partitioning of the total ice load into the different ice sheets for periods of past and ongoing rapid sea-level rise (Mitrovica *et al.*, 2001; Clark *et al.*, 2002).

The response of sea level to rapid warming

Given a broad range of emission scenarios the IPCC AR4 predicted global warming of between 1.1°C and 6.4°C during the 21st century (Solomon *et al.*, 2007). The last time that a global warming of comparable magnitude occurred was during the termination of the last glacial period (TI). The Paleoclimate Modelling Intercomparison Project (PMIP) and PMIP 2 studies concluded that global warming during TI was between 3.3°C and 5.1°C (Jansen *et al.*, 2007). Although this warming took place over a relatively long time period (between ca. 21 and 10 ka BP) it was broken up into a series of short, sharp steps on millennial to centennial timescales with significant interhemispheric differences (i.e. Bølling–Allerød and post-Younger Dryas warming, Antarctic cold reversal). Given this evidence for periods of rapid warming during TI, at least some of this warming occurred on decadal to centennial timescales. Because of the general similarity between the magnitude and rate of warming predicted for the 21st century and the warming that occurred during certain periods of TI, it is interesting to consider rates of sea-level rise during TI as a case study of the response of sea level to climate change. Here we will focus on links between Northern Hemisphere temperature reconstructions and sea level. Other studies have considered the links between Southern Hemisphere temperature reconstructions and sea level but such studies have focused on Marine Isotope Stage (MIS) 3 (Clark *et al.*, 2007; Siddall *et al.*, 2008). Nevertheless, the unknown significance of Southern Hemisphere temperature reconstructions is an important caveat for the analysis we present here.

A very general question is: what is the characteristic pattern of sea-level response to warming during TI? One can consider three basic models for this sea-level response (Fig. 2): (1) the rate of response increases exponentially with continued warming due to nonlinear feedbacks (i.e. meltwater lubrication of the ice sheet bed, destruction of buttressing ice shelves of marine-based ice); (2) tendencies for the acceleration and deceleration of the ice sheet response roughly cancel out so that the response is a steady rate over time; and (3) the response is rapid following a perturbation but then reduces over time as ice sheets reach a new steady state (i.e. subglacial hydrological system adjusts to increased melt flux, transition from marine-based to land-based ice). We compare each of these possible response scenarios to sea-level change during two periods of

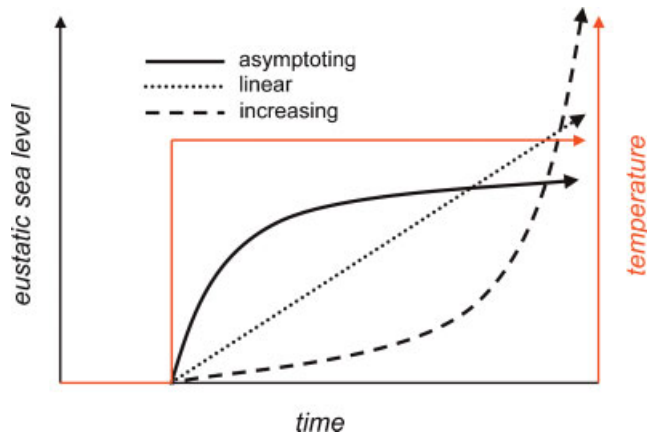


Figure 2 An illustrative sketch of three models for the time-dependent response of sea level to a perturbation in temperature. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

change during TI characterising the response of sea level to the rapid climate change during the Bølling–Allerød and post-Younger Dryas/early Holocene period (Fig. 3). We select these periods because the magnitude and rate of warming during these periods are most closely analogous to the magnitude and rate of anthropogenic warming over the coming centuries. Following the results of Fleming *et al.* (1998), sea level gradually asymptotes during the early-to-mid Holocene to reach pre-industrial levels (Fig. 3(A) and (B)). During the Bølling–Allerød and Younger Dryas, the RSL response may differ between intermediate-field (Barbados; Peltier and Fairbanks, 2006) and far-field (Tahiti; Bard *et al.*, 1996) sites, but is always either linear with respect to time or asymptotes at higher sea level. Therefore, we suggest that option 1 (exponential sea-level rise) is extremely unlikely. Note that if the climate forcing increased exponentially over time then the sea-level rise might follow this trend, but the exponential response cannot be considered a direct function of ice sheet mechanics. Improved understanding of the timing and source of meltwater pulse (MWP) 1a (Fig. 3(C) and (D) (Fairbanks, 1989; Clark *et al.*, 2002) may help to determine whether model 2 or 3 better describes ESL response.

This qualitative constraint of the evolution characteristics of future sea-level rise has important implications for our understanding of ice sheet dynamics. An exponential increase in rates of sea-level rise with respect to temperature would result in 21st-century sea-level rise an order of magnitude larger than estimates using alternative patterns of response – it is an important result that the palaeo-sea-level data rule out such a response. Evidence for the areal retreat of the North American Ice Sheets (Dyke, 2004) is in broad agreement with this conclusion (Fig. 3(A)). However, the ice sheet model used for the AR4 prediction of 20th-century sea-level rise does not capture the mode of integrated ice sheet response which is observed during the TI (Huybrechts *et al.*, 2004).

Recent work based on coral terraces U/Th dating and evidence from marine and ice core archives of climatic change during the penultimate termination (TII) and TI concluded that very similar phase relationships between North Atlantic climatic parameters occurred during both terminations, with sea-level rise lagging changes in North Atlantic surface temperature by several thousand years at the start of the interglacial period (Waelbroeck *et al.*, 2008). Previous to the last two terminations, data are restricted to ice core and marine sediment evidence. Ice core archives of glacial terminations (Kawamura *et al.*, 2007) as well as ice sheet simulations for multiple glacial terminations (Abe-Ouchi *et al.*,

2007) support the notion that the phase relationship between temperature and sea level was similar for each of the terminations.

Sea level during warm periods

Holocene

Much of the work understanding past changes in RSL has focused on Holocene records of the last 8 ka (see Long, 2000, 2001, and Edwards *et al.*, 2006, for recent reviews). The advantage of Holocene records is that insolation forcing was somewhat similar to modern values, albeit under different values for the radiative forcing due to greenhouse gases (Carlson *et al.*, 2008). The reviews of Long (2000, 2001) consider Holocene studies over two periods: late Holocene (Long, 2000) and mid Holocene (Long, 2001). Recent work on the late Holocene is particularly important for studies of future sea level because proxy measurements (salt marsh and foraminiferal transfer function techniques in particular) are increasingly of adequate temporal resolution to be compared with instrumental measurements from tide gauge records, the acceleration in RSL during the 20th century to be associated with anthropogenic global warming (e.g. Gehrels *et al.*, 2005, 2006, 2008).

During the Holocene ESL changes have been limited and isostatic sea-level rise often dominates RSL records (Fleming *et al.*, 1998). Holocene RSL records are key reference data for isostatic models (Fleming *et al.*, 1998; Peltier, 1998; Lambeck, 1999; Nakada *et al.*, 2000). As noted above, these models are in turn fundamental in correcting instrumental RSL data from tide gauge records for isostatic effects (Church and White, 2006) and therefore are of fundamental importance in understanding contemporary sea-level rise and estimating future change.

A further test of isostatic models is the RSL changes associated with abrupt changes in sea level related to the 8.2 ka event, which represented a complicated series of widespread events (Rohling and Pálike, 2005), perhaps initiated by a meltwater pulse into the North Atlantic (e.g. Schmidt and LeGrande, 2005; LeGrande *et al.*, 2006). There is increasing consensus that this event was triggered by the rapid outflow of the proglacial Lakes Agassiz and Ojibway into the Labrador Sea (Barber *et al.*, 1999). Recent work has attempted to relate RSL records with isostatic modelling of this event (Kendall *et al.*, 2008). This work has found that RSL data (e.g. Törnqvist *et al.*, 2004; Cronin *et al.*, 2007) are broadly consistent with both the suggested source and magnitude of this event.

The final demise of the Laurentide Ice Sheet has recently been quantified and modelled by Carlson *et al.* (2008). These authors found agreement between both observations of ice sheet extent and coupled ice sheet–climate model results for ESL rise of between 9 and 8.5 ka BP and between 7.6 and 6.8 ka BP as 1.3 and 0.7 m per century, respectively, due to the collapse of the Laurentide in the mid-Holocene period. Interestingly, Yu *et al.* (2007) also find evidence of a rapid increase in ESL based on RSL data from the south-eastern Swedish Baltic Sea. They ascribe this sudden rise in RSL at 7.6 ka BP to ‘a sudden increase in ocean mass, most likely caused by the final decay of the Labrador sector of the Laurentide Ice Sheet’. The corroboration of the evidence in these two independent studies seems to indicate that the rapid demise of ice sheets in a climate similar to today is certainly a possibility. However, an improved understanding of ice sheet

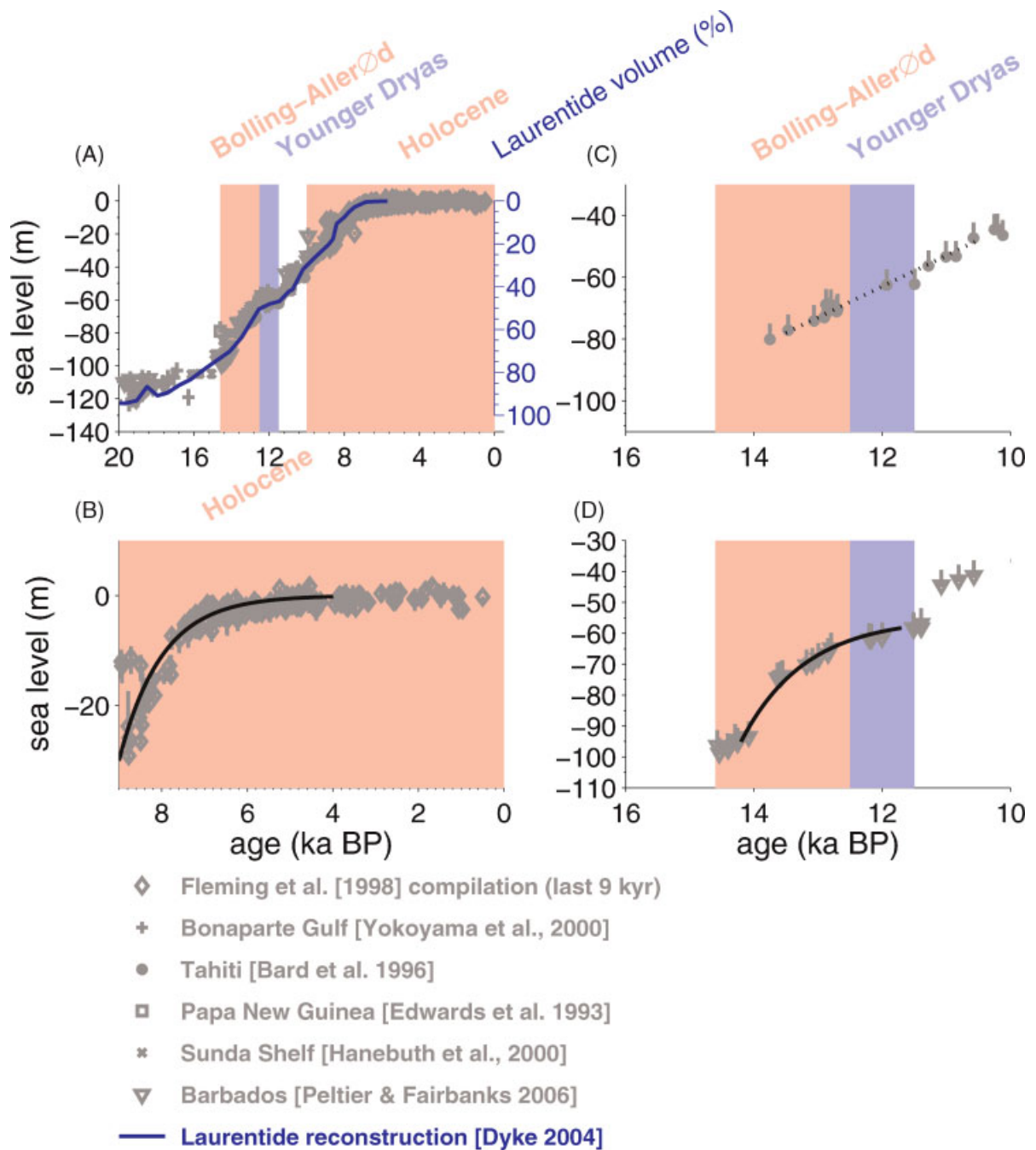


Figure 3 Sea level during TI. (A) RSL data through the termination at multiple sites, the isostatically corrected record of Fleming *et al.* (1998) compared with the reconstructed Laurentide volume after Dyke (2004) (right-hand axis). North American ice volume was approximated assuming the relationship for an ice sheet on a hard bed ($\log(\text{volume}) = 1.23(\log(\text{area})^{-1})$) (Paterson, 1994). Note that this is an approximation using a formulation developed for the Laurentide Ice Sheet only and is only shown for illustrative purposes. (B) The isostatically corrected data compilation of Fleming *et al.* (1998), corrected for glacio-isostasy, hydro-isostasy and rotational effects. (C) The medium-field response at Tahiti (Bard *et al.*, 1996). (D) The medium-field response at Barbados (Peltier and Fairbanks, 2006). Although local isostatic effects affect RSL at both sites, the accelerating response occurs at neither site – there is no evidence for an acceleration of the ice sheet response over time during TI. The black lines in B, C and D are for illustrative purposes only and are estimated ‘by eye’. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

dynamics is required before one can conclude that the Greenland or West Antarctic ice sheets will behave in a similar fashion in the future (Siddall and Kaplan, 2008).

Previous interglacial periods

RSL data from far- and medium-field sites for the last interglacial period (LIG) suggest that sea level attained close to its peak of 3–6 m above modern sea level by 126 ± 1 ka BP,

several thousand years after proxy records of temperature reached interglacial levels (Stirling *et al.*, 1998; Thompson and Goldstein, 2005; Waelbroeck *et al.*, 2008). Additional isostatic modelling is required to confirm whether these RSL estimates can indeed be considered representative of ESL estimates. Greenhouse gas and insolation forcing for the LIG were used in combination with an ice sheet–climate model and atmosphere/ocean model to reconstruct the Greenland Ice Sheet and Arctic temperatures during the LIG. Modelled Arctic temperatures and the modelled Greenland ice sheet compared favourably with temperature proxy reconstructions and the available data on

the Greenland Ice Sheet for the LIG (Otto-Bliesner *et al.*, 2006). This modelling work showed close links between Arctic sea ice and Greenland ice volume. If changes in Arctic sea ice are the primary control on changes in Greenland ice volume then insolation and greenhouse gas (GHG) forcings are equivalent providing that they both drive changes in Arctic sea ice. The sea-level equivalent ice volume contribution of the Greenland ice sheet to eustatic sea level in these simulations was 3 m. Note, however, that the ice sheet model results described by Otto-Bliesner *et al.* (2006) were not run to equilibrium. Simulations of the Greenland ice sheet during the LIG which have been run to equilibrium suggest that as much as 4 m of sea-level equivalent ice volume may have originated from the Greenland Ice Sheet during the LIG (Cuffey and Marshall, 2000; Lhomme *et al.*, 2005). This is adequate to account for the lower estimate for ESL during the LIG but not for estimates above this. Instead, higher estimates of eustatic sea level during the LIG would require additional contributions from thermal expansion of ocean water and the Antarctic ice sheets. Further work on understanding the isostatic response of the RSL estimates for the LIG is vital to confirm this assertion.

The RSL and modelling results discussed in the paragraph above tentatively suggest that for the conditions warmer than pre-industrial levels the Greenland and West Antarctic ice sheets may be vulnerable to reductions in volume. Modern observations of the Greenland and West Antarctic ice sheets consistently show evidence of rapid responses to a warming climate, including the collapse of the Larsen B ice shelf, the acceleration of ice streams and increasingly negative ice mass balance (e.g. Velicogna and Wahr, 2006; Bamber *et al.*, 2007; Rignot *et al.*, 2008; and see summary by Alley *et al.*, 2005). However, it is not clear today whether these rapid processes might have a larger-scale impact on the ice sheets with upstream repercussions, or whether they are limited to the fringes and a new stable equilibrium is achieved. Such direct observations of the modern acceleration in ice sheet dynamics constitute the foundation of a deeper understanding of the response of ice sheets to climate change but they still are of relatively short duration (typically several decades). However, because the rapid changes observed in modern ice sheets are in general agreement with palaeo-observations of the response of ESL to rising temperatures, the rapid response of ice sheets to climate change is a serious possibility. Increased understanding

of the response of ice sheets to climate change during TI will help to confirm this assertion.

Improvements in U/Th dating mean that we can begin to examine sea-level proxies as far back as MIS 15 (ca. 500–600 ka BP) (Andersen *et al.*, 2008) and tentative results have been published concerning MIS 9 (Stirling *et al.*, 2001). However, the uncertainties associated with U/Th dating increase back in time, as do the uncertainties associated with the relative sea levels associated with the deposits which are dated. Constraints on the timing of sea-level high stands during MIS 7 from diverse far- and intermediate-field sites are in broad agreement with each other and are accurate to less than a thousand years (Antonioli *et al.*, 2004; Dutton *et al.*, 2009). We note that special consideration must be given to long-term tectonic effects on isostatic sea level for older deposits and for deposits at uplifted sites. As issues with U/Th dating techniques (in particular issues around open system U/Th ages), isostatic corrections and tectonics are addressed over the next several years, this work will help us better elucidate the causes of high sea level in the past.

Summary and concluding remarks

Although none of the periods we have considered in detail here (i.e. T1, Holocene, LIG) present exact analogues for future change, each is a useful case study to understand the evolution of sea level in warmer climates (LIG), transitional climates (T1) or broadly similar climates (Holocene). Each case study has its limitations and strengths. For example, T1 represents a cooler climate with greater ice volume than at present but the magnitude and rate of warming during certain periods in the transition may be compared to changes imposed by anthropogenic greenhouse emissions. Although the magnitude of the sea-level response to a temperature perturbation must be a function of the remaining ice volume (and therefore will be reduced in the future compared to T1) there is a lot to learn from T1. The LIG had different orbital and GHG forcing to future projections but nevertheless represents an example of a warmer climate state with reduced ice volume. Finally, the Holocene climate had many similarities to today but for much of the late Holocene the climate was relatively stable and so the late

Table 1 Comparison of sea-level rise over one century for predicted and observed past changes

Source	Description	Rise per century
<i>21st-century prediction</i>		
IPCC AR4 (Meehl <i>et al.</i> , 2007)	Ice sheet model with scaled surface mass balance (no ice sheet dynamics)	0.18–0.59 m
IPCC AR4 (incl. simple dynamics)	Ice sheet model with scaled surface mass balance (accelerated ice sheet dynamics as a function of temperature)	0.18–0.68 m
IPCC TAR	Ice sheet model with scaled precipitation (no ice sheet dynamics)	0.09–0.67
Rahmstorf (2007a)	Semi-empirical model based on 20th-century observations	0.5–1.4 m
Horton <i>et al.</i> (2008)	Comparison of 11 GCMs	0.54–0.89 m
Pfeffer <i>et al.</i> (2008)	Assessment of current ice sheet dynamics	<2 m
<i>Past change</i>		
IPCC AR4 (20th century) ^a	Tide gauge data	0.12–0.22 m
Holocene (7 ka BP to pre-industrial) ^b	Isostatically corrected data compilation	0.04–0.07 m[†]
MWP 1a ^c	The most rapid period of sea-level rise during TI	3–5 m*
Mean TI ^d	Mean rate of sea-level rise during TI	1 m
Demise of Laurentide ^e	Two phases of rapid retreat of the Laurentide in the early Holocene	0.7–1.3 m

* Highest and [†]lowest rates of rise; these high values are outside of the possible range for the next century.

^aBased on Church and White (2006) tide gauge compilation.

^bFleming *et al.* (1998).

^cAs calculated by Stanford *et al.* (2006).

^dBased on 120 m sea-level rise over 12 ka.

^eCarlson *et al.* (2008).

Holocene has little to teach us about the response of sea level to large changes in global climate. However, the late Holocene provides a key baseline against which to understand future change. Furthermore, changes in RSL and ESL in the early to mid Holocene may be key to understanding future sea-level change. Here we have attempted to consider a few of the many lessons to be learnt from palaeo-data in understanding future change.

To summarise, RSL and modelling reconstructions of the LIG suggest that we are moving into a climate regime when the Greenland and West Antarctic ice sheets will become increasingly unstable (with the caveat on the need to better understand isostatic effects for the LIG). Direct observational evidence confirms this assertion. Furthermore, the response model revealed by the palaeo sea-level data suggests that sea-level rise related to current warming may be rapid at first and slow over time. Using palaeo-data and direct observations, it is possible to put loose limits on just how rapidly we might expect sea-level rise to occur over the next century. For example, one may expect sea-level rise over the next century to fall between the lower limit of 20th-century sea-level rise (0.12 m per century; Meehl *et al.*, 2007) and the sea-level rise at the conclusion of TI (1 m per century; Carlson *et al.*, 2008). Extreme lower bounds (i.e. outside the range of possibility) can be derived by pre-industrial sea-level rise during the Holocene (0.04–0.07 m per century; Fleming *et al.*, 1998), while extreme upper bounds of 2 m per century have been estimated by extrapolating the fastest observed ice stream responses to all of the ice streams of Greenland and West Antarctica (Pfeffer *et al.*, 2008) (Table 1).

We conclude by asserting that palaeo-sea-level and ice sheet reconstructions provide important constraints on future sea-level rise. RSL estimates based on palaeo-data are a necessary component to the solid Earth models of GIA used to calculate ESL rise from tide gauge data and ice sheet mass loss from satellite data. Ice sheet models must be able to capture the full range of the dynamics revealed by the palaeo-sea-level record if we are to have confidence in projections of future sea-level rise derived from them.

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