



Sea levels: science and society

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I Introduction

'Earth Science for Society' is the tagline for the International Year of Planet Earth (IYPE). This joint initiative by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Union of Geological Sciences aims to promote the activities of Earth scientists and encourage effective use of their knowledge by society. The fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) Working Group II, which considers impacts, adaptation and vulnerability, is an example of work that places current scientific understanding in a policy-relevant context (Parry *et al.*, 2007). The AR4 highlights that coasts are already experiencing adverse change linked to climate and sea level. Risks such as those associated with coastal erosion will increase over the coming decades and increased human pressures on the coastal zone will exacerbate their impacts, which will be particularly challenging for developing countries (Nicholls *et al.*, 2007).

This review focuses on sea-level change over timescales of direct relevance to human societies. It begins with an update on recent patterns and rates of sea-level rise before describing some improvements in

our understanding of ocean volume change with particular reference to the role of ice-sheet dynamics. It also examines the coastal impacts of abrupt events such as storms, hurricanes and tsunamis, before concluding with a brief comment on the relationship between sea level, coastal change and society.

II Recent rates of sea-level change

Rising sea levels increase the risk of adverse coastal impacts, such as flooding and erosion, while accelerations in the rate of rise may initiate profound morphological changes, especially in sediment limited contexts (Nicholls *et al.*, 2007). Studies of instrumental data indicate that sea-level rise during the 1990s was anomalously fast when compared to the twentieth century as a whole (Holgate and Woodworth, 2004; Bindoff *et al.*, 2007; Church *et al.*, 2008). However, rates of rise exhibit substantial natural variability at a range of timescales and so interpreting the significance of such changes is a non-trivial task (Church *et al.*, 2005; White *et al.*, 2005; Church and White, 2006). Various filtering and spectral analysis techniques can be employed to identify and remove annual to decadal fluctuations and distil longer-term non-linear trends (eg, Jevrejeva *et al.*, 2005; 2006). A broadly

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consistent pattern emerges across studies using different data compilations and methods, although Woodworth (2006) cautions that, ultimately, these studies are not truly independent, since they are based on the same global data set of tide-gauge stations with inherent limitations relating to distribution and record length.

Prior to the 1930s, the rate of sea-level rise was around 1 mm yr^{-1} , but this more than doubled during the interval between the late 1930s and late 1950s, peaking at 2.5 mm yr^{-1} , before falling to less than 2 mm yr^{-1} from the late 1950s to the 1980s (Church *et al.*, 2008). While Church *et al.* (2008) infer that the most rapid rates of sea-level rise took place during the 1990s, Jevrejeva *et al.* (2008) suggest that, when decadal variability is accounted for, the rapid rise of 2.5 mm yr^{-1} between 1920 and 1950 is the fastest rate recorded during the last 300 years. Using the long tide-gauge records of Amsterdam, Liverpool and Stockholm, Jevrejeva *et al.* (2008) go on to suggest that a significant change in the rate of sea-level rise is evident after the 1780s, equating to an acceleration of 0.01 mm yr^{-2} .

Woodworth *et al.* (2008) agree that the strongest patterns of change to emerge from tide-gauge records are the acceleration during the 1920s and 1930s, and the deceleration that took place after 1960, both of which have been commented upon in the literature for some time (eg, Gutenberg, 1941; Barnett, 1984; Woodworth 1987; 1990; Tsimplis and Baker, 2000; Tsimplis and Josey, 2001; Tsimplis *et al.*, 2005). However, their analysis shows that the precise timing and magnitude of rate changes vary between ocean basins and, while the globally averaged reconstructions of Church and White (2006) and Jevrejeva *et al.* (2006) exhibit similar patterns of acceleration and deceleration, these are strongly influenced by the tide-gauge records from Europe and North America. In contrast, some regions outside these areas exhibit changes that diverge from this 'global' pattern, and both inflexions are

not always apparent in the same record. Woodworth *et al.* (2008) conclude that divergences from these general patterns are most likely caused by the influence of factors associated with atmospheric and ocean circulation change.

Jevrejeva *et al.* (2008) note the existence of a 60–70-year periodicity in the rate of sea-level rise that extends back into the pre-industrial period. A similar pattern of variability has been noted previously in records of sea-surface temperature, sea-level pressure and European air temperature and may be indicative of an underlying Atlantic driving mechanism. One possible driver is variation in the strength of the meridional overturning circulation (Delworth and Mann, 2000), perhaps through the advection of density anomalies (Dijkstra and Ghil, 2005), although observational data are at present insufficient to determine this, while model simulations do not reproduce strong patterns on these timescales (Knight *et al.*, 2005).

Over shorter timescales of years to a decade or so, other processes become significant. For example, the reduction in the rate of sea-level rise that occurred during the 1960s coincides with a series of explosive volcanic eruptions that are inferred to have produced cooling and contraction of the upper ocean (Church *et al.*, 2005; Gleckler *et al.*, 2006a; 2006b; Jevrejeva *et al.*, 2006), although Woodworth *et al.* (2008) note that larger contributions are required to explain the post-1960 flattening observed in many individual records. Circulation changes associated with large-scale atmospheric modes, such as the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO), are significant since they can result in the redistribution of water masses within an ocean basin (Trenberth *et al.*, 2002; Jevrejeva *et al.*, 2006; Baines and Folland, 2007). Miller and Douglas (2007) suggest that gyre-scale wind forcing may potentially cause gyres to spin up or down causing water to migrate into or out from their centres. Consequently, average basin-wide

trends may be hard to measure from coastal tide gauges, and variability between basins further complicates the application of approaches that rely on recent spatial patterns inferred from satellite data (eg, Church and White, 2006).

Improvements in our understanding of these kinds of change will rely on the development of new records covering the last century or more. Tide-gauge 'archaeology' may provide one means of improving instrumental data coverage (Church *et al.*, 2008; Woodworth *et al.*, 2008), but high-precision geologically based reconstructions also have an important role to play. In low latitudes, micro-atolls can provide decimetre and multidecadal- to century-scale relative sea-level (RSL) reconstructions which, given favourable conditions of growth and preservation, may record subtle variability associated with ENSO-related changes in sea-surface temperature and wind stress (eg, Goodwin and Harvey, 2008). In higher latitudes, microfossil-based investigations of salt-marsh sediments, such as those reviewed in the previous progress report, can produce records of similar resolution (Edwards, 2007). In a recent example of this approach, Gehrels *et al.* (2008) produce a 500-year RSL record from southeastern New Zealand, generated from foraminifera-based sea-level index points and a composite chronology established from AMS radiocarbon dating, lead concentrations, stable lead isotopes, pollen markers, charcoal concentrations and caesium-137.

The production of a robust chronology is a critical element in developing this type of high-resolution reconstruction. Traditional sea-level investigations have relied on the use of radiocarbon dating, but this has reduced effectiveness in the last few hundred years. Shorter-lived radionuclides (eg, Pb^{210} and Cs^{137}) can assist in developing chronologies covering the last 100 years, but are associated with limitations such as the postdepositional migration of caesium under certain conditions (eg, Smith, 2001; Harvey *et al.*, 2007). An

alternative potential approach for dealing with radiocarbon-based chronologies spanning the last century is 'bomb-spike' calibration (Turetsky *et al.*, 2004). This approach is based upon the fact that there is a rapid increase or spike in atmospheric radiocarbon after AD 1950 as a consequence of nuclear weapons testing, and this has been used to constrain the age of organic-rich sediments (Goodsite *et al.*, 2001; McGee *et al.*, 2004). Marshall *et al.* (2007) have successfully applied this approach to salt-marsh sediments and show how the careful combination of multiple lines of dating evidence can result in an improved, more secure accumulation history. Their analysis, which includes the use of high-precision (extended counting) radiocarbon dates to reduce age uncertainties, also indicates that concerns surrounding the use of Pb^{210} for dating salt-marsh sediments are well founded.

III Ocean volume change

The pronounced variability of sea level over a range of timescales complicates reliable determination of changes that are driven by rising temperatures alone. The recent debate surrounding attempts to infer future sea-level rise from global temperature also illustrates that conclusions are sensitive to the choice of data manipulation and statistical techniques used (eg, Rahmstorf, 2007a; 2007b; Holgate *et al.*, 2007; Schmith *et al.*, 2007). Thermal expansion and melting land-based ice appear to be the main factors contributing to both the sea-level rise observed during the twentieth century, and the rise predicted for the twenty-first century (Bindoff *et al.*, 2007; Meehl *et al.*, 2007; Church *et al.*, 2008). Improvements in the estimates of both terms are necessary if the sea-level budget is to be closed satisfactorily and projections of future sea-level rise are to be better constrained (see Edwards, 2007). In some cases, improvements can come from better observational data and alternative methods of analysis. For example, the recent identification of a systematic warm bias

in expendable Bathymetric Thermograph (XBT) data (Gouretski and Koltermann, 2007; Wijffels *et al.*, 2008) means that earlier estimates of ocean thermal expansion require revision. Domingues *et al.* (2008) correct for this bias in their revised estimate of upper ocean thermal expansion, resulting in a 40% reduction for the period 1993–2003. They also use an alternative statistical approach to deal with the sparse nature of the observational database, and conclude that for the period 1960–2003 previous estimates of thermal expansion for the upper 700 m were underestimated by around 50%. The authors note that their new globally averaged estimates are almost identical to the rates presented by Jevrejeva *et al.* (2006), although they diverge from satellite altimeter observations after 1999 for reasons that are not yet understood.

In other cases, some fundamental advances in the current state of knowledge are required before processes are sufficiently well quantified that they can be reliably modelled. Perhaps the best example of this is the uncertainty surrounding the dynamic nature of ice-sheet response to climate change (Meehl *et al.*, 2007). One of the potential mechanisms that may bring about rapid ice-sheet change is the introduction of meltwater to the base of an ice sheet, lubricating it and resulting in an acceleration and increased discharge (Joughin *et al.*, 2004; Rignot and Kanagaratnam, 2006). Recent studies suggest that it is not simply the amount of meltwater reaching the base that is important, but rather how this water supply varies through time and its relationship to the capacity of the subglacial hydraulic system. Bartholomaeus *et al.* (2008) show that glacier velocity increases when englacial and subglacial storage is increasing, but that sustained high rates of supply do not produce continued rapid motion. They suggest this is because subglacial hydraulic systems adjust to accommodate increased water inputs. Consequently, accelerations arise when the subglacial hydraulic efficiency is insufficient

to handle the increased volumes of water arriving at the base, and persist until the drainage system evolves to accommodate the increased discharge.

An important implication of this research is that large pulses of meltwater to the base of an ice sheet may be a critical factor in determining dynamic ice-sheet change. In Greenland, one way that this sort of injection of meltwater may occur is via the draining of surface meltwater ponds through cold basal ice (van der Veen, 2007). Das *et al.* (2008) present a dramatic illustration of this process by capturing the catastrophic drainage of a large (~2 km diameter) supraglacial lake, which emptied in less than 1.5 hours and produced a flow rate greater than that of Niagara Falls. The water, which cut through almost a kilometre of ice, lifted and moved the ice sheet and resulted in a short-lived but substantial increase in the average daily displacement. Thousands of lakes form on the Greenland Ice Sheet (GIS) during the ablation season (Box and Ski, 2007), and any increase in the frequency, duration or magnitude of pulsed drainage to the bed associated with climate warming may therefore influence GIS dynamics (Bartholomaeus *et al.*, 2008; Das *et al.*, 2008).

However, while satellite data indicate that during the summer high melt associated with drainage of supraglacial lakes causes the western flank of the GIS to accelerate by between 50 and 100%, relative changes in the outlet glaciers, such as Jakobshavn Isbræ which has been the focus of particular attention, are actually much smaller and more spatially complex (Joughin *et al.*, 2008). Instead, seasonal speedup is in phase with changes in ice-front position which may indicate that backstress from buttressing sea ice is a more significant control on the accelerations of tidewater outlet glaciers. Consequently, Joughin *et al.* (2008) conclude that while increased melting due to warming may influence large areas of the GIS, such as those to the south of Jakobshavn where there are comparatively few outlet glaciers,

its effect on the most rapidly flowing ice is more modest and the impacts on the future evolution of the GIS, while substantial, are unlikely to be catastrophic. Similarly, while van de Wal *et al.* (2008) report rapid ice velocity responses to meltwater input at the timescale of weeks, annual velocities show little variation, supporting the view that accelerations are transient responses while the englacial system reconfigures to deal with changing meltwater volume.

In Antarctica, most land-based ice is believed to be frozen to the bedrock so the potential for meltwater-induced acceleration is reduced. Instead, attention has tended to focus on the fact that the base of much of the West Antarctic Ice Sheet (WAIS) lies below sea level. This makes it potentially sensitive to ice-sheet thinning and sea-level rise, although recent research questions the extent of this instability (Anderson, 2007). However, the WAIS is situated over a crustal rift that is associated with volcanism (Winberry and Anandakrishnan, 2004) and several volcanoes protrude through the ice sheet (Wilch *et al.*, 1999). In the event of an eruption, the altered thermal regime may release significant volumes of meltwater into the system, lubricating the bed and increasing the potential for a surge (Vogel, 2008). Subglacial volcanoes therefore have the potential to influence ice dynamics and the stability of the WAIS (Vogel and Tulaczyk, 2006; Corr and Vaughan, 2008). New airborne radar data have recently been used to identify a volcano beneath the WAIS from a strong reflector interpreted as a tephra layer (Corr and Vaughan, 2008). While this eruption, which is dated to 207 BC \pm 240 yrs and correlated with strong conductivity signals detected in ice cores (Hammer *et al.*, 1997; Kurbatov *et al.*, 2006), appears to have had only limited impact on the dynamics of the WAIS, it raises the possibility of more widespread volcanism beneath the WAIS which may be revealed by reinterpreting similar radar data (Vogel, 2008).

Palaeoenvironmental research provides baseline information against which the stability of the modern ice sheets can be assessed. A growing body of sea-level data is being collected from the logistically challenging high-latitude regions which, when analysed in combination with geophysical models of glacio-isostatic adjustment (GIA), can be used to provide important constraints on the pattern and timing of past ice-sheet changes. In southern and southeastern Greenland, marine limit and isolation basin data reveal lateglacial and early-Holocene RSL falls driven by rapid isostatic rebound (Bennike *et al.*, 2002; Sparrenbom *et al.*, 2006; Long *et al.*, 2008). These new data do not fit well with existing GIA models (eg, Tarasov and Peltier, 2002; Huybrechts, 2002; Fleming and Lambeck, 2004), commonly underestimating the height of the marine limit by several tens of metres. These field data may indicate that current models underestimate the extent and thickness of Greenland ice at the Last Glacial Maximum (LGM), and that once melting commenced it proceeded more rapidly than previously believed (Sparrenbom *et al.*, 2006; Long *et al.*, 2008).

Similar misfits between simulated and reconstructed RSL are evident in data from Antarctica where Bassett *et al.* (2007) conduct a series of sensitivity analyses to examine the possibility that Antarctic melting is a plausible, dominant source of meltwater pulse (MWP) 1a. They use the 'sea-level fingerprinting' approach (see Edwards, 2005) to compare the contrasting patterns of simulated RSL change produced by two end-member scenarios in which all meltwater is supplied from either a Northern or Southern Hemisphere source. While the Southern Hemisphere scenario performs best, the authors caution that limitations in the available field data preclude a definitive conclusion being drawn. However, neither model produces a reasonable match to field data from half of the study sites examined, underpredicting the isostatic component of RSL

change in the Antarctic Peninsula and the Sôya Coast (East Antarctic Ice Sheet). Once again, this suggests that thicker ice may have been present in potential meltwater source regions such as the Antarctic Peninsula (Bentley, 1999; Huybrechts, 2002; Heroy and Anderson, 2005). However, recent work by Heroy and Anderson (2007) using marine cores and seismic data seems to indicate that retreat of grounded ice in this area occurred several thousand years earlier than the estimates used by current GIA models. While there are substantial challenges associated with establishing a reliable chronology from these data, they may limit the extent to which additional ice can be added in this area. Nevertheless, Heroy and Anderson (2007) agree that some melting from the Antarctic Peninsula did contribute to both MWP1a and MWP1b, even if the volumes concerned may have been relatively small.

IV Extreme events

Much of the interest in meltwater pulses and ice-sheet instability stems from the fact that they can produce rapid rates of sea-level rise several times greater than the longer-term average. Abrupt but short-lived changes can also be destructive, and coasts are vulnerable to impacts from extreme events that perturb water levels for comparatively brief intervals. For example, it is estimated that 120 million people are at risk from tropical cyclone hazards which killed 250 000 people in the last two decades of the twentieth century (Nicholls *et al.*, 2007). Tropical cyclone Nargis struck the low-lying Irrawaddy delta in May 2008 with devastating consequences that were reminiscent of the Great Sumatra-Andaman Indian Ocean tsunami of December 2004 (Lay *et al.*, 2005). Over 130 000 lives were lost, and a further 1.5 million people severely affected by the flooding, destruction of homes, infrastructure, farms and fisheries (Webster, 2008). Deltas are particularly vulnerable since increases in sea level are compounded by land

subsidence and human interference such as sediment trapping by dams (Bird, 2000; Dixon *et al.*, 2006; Ericson *et al.*, 2006; Church *et al.*, 2008). Given a sea-level rise of 2 mm yr⁻¹, it is estimated that over 8.5 million people living in deltaic regions will be affected by the middle of this century (Ericson *et al.*, 2006) and this figure will be higher if the incidence of extreme events increases. While these impacts are likely to be greatest in the densely populated Asian megadeltas (Nicholls *et al.*, 2007) the destruction caused by Hurricane Katrina in 2005, which resulted in over 1800 deaths (Graumann *et al.*, 2005), and economic losses estimated at over 100 billion US dollars (NOAA, 2007), illustrates the general vulnerability of inhabited low-lying areas.

Limitations in instrumental data mean that at present there is still some controversy concerning whether or not intense cyclones are becoming more common (Emanuel, 2005; Webster *et al.*, 2005; Chan, 2006; Mann and Emanuel, 2006; Landsea *et al.*, 2006; Holland and Webster, 2007). Elsner *et al.* (2008) conclude that, while average trends vary between basins, Atlantic tropical cyclones have increased in strength in recent years. A more widespread increasing trend is noted in the wind speeds of the strongest cyclones, which is consistent with the idea that warmer seas will result in more violent storms. However, large uncertainties are associated with recent model-based investigations of future trajectories of change, with some studies showing a modest decrease in the activity of Atlantic hurricanes during the twenty-first century (Knutson *et al.*, 2008), while others note that the sign and magnitude of predicted changes varies considerably between ocean basins and from model to model (Emanuel *et al.*, 2008).

Palaeoenvironmental records are potential tools for evaluating the risk posed by extreme events since they can be examined to infer longer-term trends in activity during the Holocene (eg, Liu and Fearn 1993; 2000; Donnelly *et al.*, 2001a; 2001b). Donnelly

and Woodruff (2007) use coarse sediment layers washed over a coastal barrier into a lagoon to examine hurricane activity in the Caribbean during the last 5000 years. They infer that these events have more than local significance by the similarity in timing exhibited between phases of enhanced or reduced storm inputs recorded at the study site, and similar evidence of hurricane landfalls reported from records in Florida and Long Island Sound (Liu and Fearn, 2000; Scileppi and Donnelly, 2007). Together these data suggest that the last millennium was a comparatively quiescent period for hurricane activity until around AD 1700 when a more active regime develops. The similarity with proxy records of precipitation leads Donnelly and Woodruff (2007) to conclude that hurricane variability is probably modulated by atmospheric dynamics associated with ENSO and the West African monsoon, rather than having a simple relationship to sea-surface temperature. Systematic changes in site sensitivity through time, such as changes in the morphology of the protective barrier, may distort hurricane intensity records, and so further work is required to see if the temporal patterns revealed are evident in more study sites along the coasts of the Caribbean and the USA (Donnelly and Webb, 2004; Scileppi and Donnelly, 2007).

Storm deposits can be confused with those associated with tsunamis. While both phenomena may have devastating coastal impacts, it is important to differentiate between their imprints in the geological record if reliable inferences of recurrence and risk are to be made from them. Consequently, a considerable body of literature is now devoted to developing criteria by which such sedimentary deposits may be discriminated (Dawson and Shi, 2000; Dominey-Howes, 2002; Dominey-Howes *et al.*, 2006; Tappin, 2007; Dawson and Stewart 2007a; 2007b). Fine-grained, sandy sediments have been the focus of most attention since a combination of data including spatial distribution, sedimentology and microfossil content can be

applied to critically evaluate these deposits (eg, Nanayama *et al.*, 2003; Cisternas *et al.*, 2005; Nanayama and Shigeno, 2006; Morton *et al.*, 2007; Sawai *et al.*, 2008). Kelletat (2008) contends that this emphasis has been at the expense of coarser deposits which are often overlooked or discounted despite an expanding body of work that employs boulder accumulations as evidence of tsunami deposition (eg, Scheffers, 2002; Scicchitano *et al.*, 2007; Mastronuzzi *et al.*, 2007; Scheffers and Scheffers, 2007; A. Scheffers *et al.*, 2008; S.R. Scheffers *et al.*, 2008).

It is possible that coarse material has greater potential for preserving a tsunami imprint, since recent work examining deposits left by the December 2004 tsunami suggests that its geomorphological and sedimentological record appears limited and is likely to be rapidly lost as it is modified by normal marine processes (Keating *et al.*, 2005). However, while boulder-based research has great potential, it currently lacks the multiple strands of evidence that assist in developing clear tsunami fingerprints from finer deposits. Often deposit formation is inferred from calculations of boulder mass and the size of wave required to move them (eg, Nott, 2003). However, the equations used to calculate wave height only deal with a subset of possible transport mechanisms, and Spiske *et al.* (2008) demonstrate that even when these equations are applied wave heights can be significantly overestimated by failing to accurately measure boulder volume and porosity. On the basis of observations made in the wake of the Indian Ocean tsunami, Paris *et al.* (2008) conclude that, while the spatial distribution and position of boulders can provide information on the direction and transport mechanism of tsunamis, at present boulder fields do not appear to be powerful indicators of palaeotsunami magnitude. It is clear that more detailed studies are now required, especially since in some instances, where additional analysis has been undertaken, no support is found for

the proposed tsunami origin of deposits (eg, Dominey-Howes *et al.*, 2006).

V Discussion

The significance of sea-level change is self-evident given that human societies are intrinsically linked with the coast. Almost a quarter of the world's population lives within 100 km of the sea (Small and Nicholls, 2003). Within this relatively thin band, population densities are three times the global average (including 12 of the world's 16 largest cities, each containing over 10 million inhabitants), and by the 2080s the coastal population may reach in excess of 5 billion people (Nicholls *et al.*, 2007).

Despite this significance, the uncertainties attached to projections of future sea-level rise remain comparatively large, and there are some indications that the AR4 estimates may be somewhat conservative based on evidence from recent trends (Rahmstorf, 2007a; Jevrejeva *et al.*, 2008). While the potential for rapid rises of several metres during the twenty-first century has been raised (Otto-Bliesner *et al.*, 2006; Overpeck *et al.*, 2006; Hansen *et al.*, 2007), a recent study that considers the possible upper limits of land-ice contributions concludes that rises in excess of 2 m by 2100 are physically impossible on glaciological grounds (Pfeffer *et al.*, 2008). Instead, Pfeffer *et al.* (2008) suggest that 0.8–2.0 m of sea-level rise during the twenty-first century is a plausible initial estimate that includes the influence of increased ice dynamics.

Further work is required to balance the sea-level budget through improved observations of recent sea-level change and better quantification of the factors contributing to it. In addition to thermal expansion and the role of ice sheets outlined above, the contributions from other sources such as glaciers and ice caps are also significant areas for study (Lemke *et al.*, 2007; Meier *et al.*, 2007; Pfeffer *et al.*, 2008). Changes in terrestrial storage are an often overlooked and poorly quantified factor, but one that recent research

suggests may have important implications for understanding twentieth-century sea-level change. Chao *et al.* (2008) estimate that during the past half-century dam-building has been responsible for impounding increased volumes of fresh water, equivalent to 0.55 mm yr⁻¹ of sea-level rise. If correct, this could indicate that some of the variations in rates of sea-level rise noted from tide gauges may reflect 'artificial' rather than 'natural' processes. While this reduction may be offset by increased supply from underground sources, the magnitude of such inputs is largely unknown (Huntington, 2008).

Improvements in instrumental data, such as those provided by the expanding network of tide gauges under the Global Sea Level Observing System programme (<http://www.gloss-sealevel.org>); the recently achieved global (ice-free) ocean coverage of Argo floats (<http://www.argo.net>); and the latest generation of satellite platforms such as the Gravity Recovery and Climate Experiment (GRACE) (<http://www.csr.utexas.edu/grace>), and the new Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission (<http://www.esa.int/SPECIALS/GOCE>); will be key to advancing our understanding of sea-level change in the twenty-first century. As the quality of observing systems improves, new opportunities for investigation will arise, such as the potential to examine changing terrestrial surface water levels or sea levels associated with oceanic mesoscale variability (Alsdorf *et al.*, 2007; Church *et al.*, 2008).

The GIA signal is a critical element in decoding ice-sheet mass change from GRACE data, since postglacial rebound is the largest source of uncertainty in areas such as the East Antarctic Ice Sheet (Velicogna and Wahr, 2006). New RSL data from high-latitude studies have an important role to play in refining models of GIA, as do similar studies from formerly glaciated areas. Interestingly, several recent papers seem to require larger, more extensive ice sheets than previously thought, and indicate that these

then melted away rapidly during the early stages of deglaciation (Bassett *et al.*, 2007; Brooks *et al.*, 2008; Long *et al.*, 2008). In some instances, significant misfits remain between field data and model simulations and this has led some to suggest that the current generation of models fail to reproduce the rate and magnitude of RSL change immediately following deglaciation (McCabe, 1997; 2008a; 2008b; Cooper *et al.*, 2002; Kelley *et al.*, 2006; McCabe *et al.*, 2007). Alternatively, some of these misfits may be associated with the limited precision of available sea-level data, resulting in erroneous RSL reconstructions (Edwards *et al.*, 2008). In either event, further work is required to continue to refine GIA model simulations which play a critical role in interpreting the spatial patterns of sea-level change, and in converting global-scale projections of future sea-level rise into ranges that are appropriate at regional or local scales.

In the UK, IPCC projections are tailored for regional use as part of the UK Climate Impact Programme (UKCIP). This process is underpinned by RSL data collected by numerous Earth scientists and summarized most recently by Shennan and Horton (2002) in their map of RSL change. UKCIP use this map to adjust IPCC projections by accounting for differential vertical land movements related to ongoing GIA. However, this approach implicitly assumes that no significant sea-level change has taken place during the last 4000 years and, while changes during this interval are poorly quantified, instrumental records indicate this assumption is invalid for at least the last century (Gehrels and Long, 2008). New sea-level data will continue to refine the patterns and rates of RSL change (eg, Massey *et al.*, 2008) and UKCIP projections will need to be updated to account for these advances in understanding. While these estimates provide an indication of the chronic effects of sea-level rise, the impacts of any associated change in extreme events must also be considered (eg, Woodworth *et al.*, 2007) since

these often have dramatic impacts on coastal environments.

In addition to projections of future sea-level rise, practitioners require much better information on precisely how quoted figures will translate into tangible effects in their area, such as shoreline retreat, erosion and flooding (Tribbia and Moser, 2008). The complex nature of dynamic coastal systems means they often exhibit non-linear responses to change, characterized by sensitivity to critical thresholds relating to rates of sea-level rise and sediment supply (Dronkers, 2005). Consequently, while coastlines may continually adjust towards a dynamic equilibrium (Woodroffe, 2003), this process is commonly punctuated rather than progressive, and may also deviate abruptly and significantly (although sometimes more ephemerally) to extreme events. As a result, the relationship between sea-level rise and coastal response is difficult to quantify (Cowell *et al.*, 2006), and extrapolation of past rates to infer future erosion trends is unreliable (Nicholls and Stive, 2004). This situation is compounded by human modification of coastal and estuarine environments which has become increasingly profound in recent centuries (Lotze *et al.*, 2006).

The Louisiana coast, incorporating the Mississippi delta, illustrates the challenges associated with vulnerable deltaic plains. Since the 1970s, 90% of the Louisiana shoreline has been eroding at an average rate of 12.0m yr⁻¹ (Morton *et al.*, 2004), while over 1500 km² of coastal wetland were transformed into open water between 1978 and 2000 due to the combined effects of sediment starvation, increased salinity and water level (Barras *et al.*, 2003). Superimposed upon this backdrop of progressive change are the impacts of extreme events such as Hurricane Katrina which resulted in the loss of an estimated 388 km² of land in the Mississippi delta area (Barras, 2006), and the destruction of around 50% of the Chandeleur Islands, southeast of New Orleans (Nicholls *et al.*, 2007). The

complexity of coastal processes is illustrated by the fact that while sediment starvation due to flood protection measures may contribute to wetland loss in the Mississippi delta, Turner *et al.* (2006; 2007) contend that sediment deposition by hurricanes is the most significant supplier of inorganic material to landward areas where fluvial inputs are intermittent. While their calculations have been criticized (Törnqvist *et al.*, 2007), these results may indicate that although hurricanes are most commonly associated with destructive impacts they may in fact play an important role in promoting wetland growth and stability in the face of rising RSL. If correct, this may indicate that the organic component of the wetland ecosystem is the key to understanding its longer-term health.

The importance of organic coastal sediments is further highlighted by palaeo-environmental studies that reveal longer-term changes relating to processes such as sediment compaction. Despite the complexity of establishing reliable sediment chronologies in deltas due to sediment storage and remobilization (Stanley and Hait, 2000), careful analysis of basal peat can produce relatively precise records of RSL change which permit inferences about longer-term stability to be made (eg, Törnqvist *et al.*, 2004a; 2004b; 2006). Gonzalez and Törnqvist (2006) and Törnqvist *et al.* (2006) use RSL data from coastal Louisiana to examine the stability of the Mississippi delta area, concluding that subsidence and wetland loss is likely to be due to the compaction of Holocene sediments. While this assertion is contested (Blum *et al.*, 2008; Donnelly and Giosan, 2008) the concept of sediment compaction as a driver of coastal change is not restricted to the Mississippi delta. Long *et al.* (2006) examine the late-Holocene sediments of Romney Marsh in southern Britain, and propose that sediment surface lowering due to compaction was a critical process that effectively resulted in the 'self-destruction' of wetlands via dewatering, desiccation and loading by tidal water and

clastic sediments. These internal controls on coastal evolution highlight the problems of inferring RSL oscillations on the basis of interchanges between organic and minerogenic sequences. This is particularly problematic when attempting to correlate similar sequences across large geographical areas since this requires assumptions of stability that may be erroneous (eg, Behre, 2007; Vink *et al.*, 2007).

VI Concluding remarks

Sea-level research encapsulates the aims of IYPE by bringing together Earth scientists from a wide range of disciplines, and combining their knowledge to address an issue with direct consequences for society. The ocean has a long 'memory' which means our actions today will have repercussions that extend several centuries into the future (Meehl *et al.*, 2005). Similarly, in order to fully understand modern sea level, it is necessary to peer backward in time and piece together the sequence of events leading up to the present. Geologically based reconstructions of past RSL provide one means of achieving this, and associated palaeoenvironmental information can provide evidence of coastal response to these changes. In some cases, this information can even be used to examine possible human responses to environmental change (eg, Turney and Brown, 2007; Chen *et al.*, 2008).

Producing new information is not the entire story, however, since an apparent disconnection exists between science and decision-making which results in many management decisions being made without significant scientific input (Sarewitz and Pielke, 2007). Tribbia and Moser (2008) note that scientists often publish in areas that are not commonly read by decision-makers, while many managers have insufficient time, resources or expertise to analyse and assess all the new information that is produced. This situation is exacerbated where scientists fail to produce the kinds of information that managers require (McNie, 2007), and when

managers turn to the media leaving valuable academic resources untapped (Tribbia and Moser, 2008).

While palaeoenvironmental studies can produce models of long-term coastal evolution covering several thousands of years (eg, Long *et al.*, 2000; Allen, 2003; 2005), coastal managers face the challenge of interpreting these in light of projections of future sea-level rise and contemporary process studies that commonly cover timescales of a few years or less (Rodriguez *et al.*, 2001; Storms *et al.*, 2002; Stolper *et al.*, 2005; Nicholls *et al.*, 2007). Similarly, improved estimates of sea-level rise are not easily translated into key parameters such as erosion and coastal retreat. Simplistic models, such as the Bruun rule, are increasingly regarded as being inadequate due to their inability to capture important feedback processes (Cooper and Pilkey, 2004; Stive, 2004). Process-based numerical models developed for particular shoreline types offer an alternative (eg, Walkden and Dickson, 2008), but are not applicable in all cases.

While it is important that academic research is not simply reduced to the status of a service-provider for decision-makers, it is clear that improved communication and closer cooperation between actors is important if society is to make maximum use of scientific knowledge. One possible means by which this may be achieved is through the use of 'boundary organizations' which mediate in the 'co-production of knowledge' that is of greater utility to a wider audience (Guston, 2001). Geographers are particularly well qualified to act as translators between the scientific and social arenas, and partnerships between science, government, business and community sectors will be critical in addressing sea-level rise and its impacts during the twenty-first century (Church *et al.*, 2008).

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