Progress report

Sea levels: change and variability during warm intervals

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I Introduction

The challenges associated with understanding precisely how climate affects sea level have been regular features of progress reports since the 1990s (eg, Woodroffe, 1993; 1994; Woodroffe and Nash, 1995; Long, 2000; 2001; 2003; Edwards, 2005). Warm intervals like the Holocene are generally associated with high sea levels, but quantifying precisely how high these levels were, how quickly they were attained and what volumes or sources of water were involved remain important foci of research. These issues are of critical importance given current concerns about climate change, and the fact that oceanic thermal inertia seems to mean future rises are inevitable (Wigley, 2005). This review examines developments in our understanding of interglacial, postglacial and recent changes in sea level, with particular reference to the information provided by sea-level highstands. These are compared with new data from a series of studies concerned with changes in the Greenland and Antarctic ice sheets. The picture of variability emerging poses particular challenges for models seeking to predict future trajectories of change.

II Sea-level highstands

Marine oxygen isotopes provide a globally integrated framework of sea-level change during the Quaternary (Lisiecki and Raymo, 2005). These data underpin the view that successive sea-level highstands, caused by melting terrestrial ice and associated with changes in atmospheric composition, are in some way paced by an orbital forcing (Ruddiman, 2003). The resulting general picture is of sea level oscillating by around 100 m during the Quaternary, superimposed upon a longer-term downward trend from Cretaceous highs of 50 to 100 m above present (Miller *et al.*, 2005).

Like most proxy data, oxygen isotopes provide a composite signal that requires deconvolution and calibration (Sidall, 2005). Current work is seeking to improve the resolution and length of isotope-derived sea-level records by combining foraminiferal data with palaeoceanographic and climate models (eg, Sidall *et al.*, 2003; Bintanja *et al.*, 2005). Nevertheless, despite increases in resolution, the 'global' nature of these records means they cannot be used to investigate the spatial variability that is critical to understanding sea-level change at

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timescales of 10^3 years or less. Instead, attention is turned to sea-level imprints that are biologically and physically etched onto the Earth's surface at particular locations. Highstand indicators, such as coral reef terraces, wave-cut platforms and tidal notches, are used to refine the general patterns of sea-level change revealed by oxygen isotopes, and provide additional details relating to the height, number and timing of these variations. Improving the number, distribution and quality of highstand records was a key objective of International Geoscience Programme (IGCP) 437 *Coastal Environmental Change During Sea-Level Highstands* (Fletcher and Murray-Wallace, 2002; Long *et al*., 2002; Murray-Wallace *et al*., 2003; Radtke *et al*., 2004; Mastronuzzi *et al*., 2005). A number of studies have revealed a surprising degree of sea-level variability at suborbital timescales, which may have important implications for the relationships among climate, the cryosphere and sea-level.

1 Interglacial sea levels
Interglacial highstands, reflecting earlier climate/cryosphere/sea-level relationships, provide a useful reference against which current and future change can be assessed. Higher than present relative sea levels (RSL) can be deduced from depositional indicators (eg, beach and lagoon sediments), erosional indicators (eg, marine terraces, tidal notches) and biological indicators (eg, boring or encrusting organisms). In tectonically stable far-field areas, such as southern Australia, RSL changes are often considered synonymous with eustatic change, although even these areas may be subject to localized neotectonic influences (Murray-Wallace, 2002). Elsewhere, eustatic sea-level changes are calculated after correction for land uplift or subsidence. In classic sites like Barbados, long-term uplift produces 'staircases' of raised shorelines that permit the separation of multiple highstands (eg, Blanchon and Eisenhauer, 2001). Similarly, diving, remotely operated vehicle and submersible observations can be used to investigate presently submerged sequences (eg, Webster *et al*., 2006). While

glacio-hydro-isostatic processes mean that no single value of sea level is appropriate for all sites around the world, detailed local records in combination with geophysical models can be used to examine ocean volume changes.

Coral reefs have contributed greatly to the study of interglacial sea levels since they are directly dateable and their vertical relationship with sea level can be quantified. Certain species, such as the reef-crest coral *Acropora palmata*, are especially useful in this regard, but care needs to be taken in order to discriminate *in-situ* colonies from storm-ridge deposits (eg, Blanchon and Perry, 2004). Similarly, when interpreting sea-level changes from morphostratigraphic data, a detailed programme of sampling is required to differentiate and date depositional features, such as reef terraces, from erosional ones, such as wave-cut platforms (Schellmann and Radtke, 2004).

Refined local records of change, facilitated by advances in dating since the pioneering studies of the 1960s and 1970s, are now revealing considerable sea-level variability at suborbital timescales. In Barbados, a series of 13 reef stages extend 120 m above modern sea level. Re-examination of the 'standard traverses' used in a number of sea-level studies indicates that multiple phases of reef formation are associated with the last interglacial (MIS 5e) and glacial interstadials (MIS 5a and 5c) (Schellmann and Radtke, 2004; Schellmann *et al*., 2004; Potter *et al*., 2004). In fact, Schellmann and Radtke (2004) suggest that multiple highstands were also experienced during earlier interglacials (MIS 9 and 11). Deciphering this variability is made possible by improvements in electron spin resonance (ESR) and thermal ionization mass spectrometry (TIMS) uranium-series dating of corals, which reduce age uncertainties and permit the temporal separation of closely spaced coral terraces. Comparative studies that examine different dating methods such as TIMS, ESR and radiocarbon (each of which have their own set of limitations), are important in this refining process (eg, Radtke *et al*., 2003; Schellmann

et al., 2004; Chiu *et al*., 2006), although the manner in which this is undertaken is not always agreed (eg, Fairbanks *et al*., 2005; Reimer *et al*., 2006).

In addition to improving the precision of dating methods, enhanced resolution can be achieved by increasing the number and distribution of dated indicators. In a recent paper, Thompson *et al*. (2003) attempt to 're-write' the decay equations used in U/Th dating of coral to correct for errors due to open-system behaviour in some samples (see Walker, 2005). Previously, extensive screening was required to remove potentially erroneous data, in extreme cases constituting up to 90% of available dates. The expanded database arising from the inclusion of corrected coral ages allowed Thompson and Goldstein (2005) to construct a high-resolution sea-level curve from Barbados covering the previous two interglacials (MIS 5 and 7). Once again, their data reveal considerable variability, with large, rapid changes of between 6 to 30 m occurring at rates approaching 10 mm/yr.

Multiple highstands during warm intervals are not restricted to Barbados or coral-based indicators. Similar variability during MIS 5 has been reported from New Guinea (Esat *et al*., 1999), and Haiti (Dumas *et al*., 2006), while sediment from the Bahamas Banks reveals an additional highstand associated with MIS 7 (Henderson *et al.*, 2006). Elsewhere, morphological and facies analysis of Spanish raised marine terraces suggest up to three highstand deposits are associated with MIS 5e (Zazo *et al*., 2003). Establishing a chronology is a particular challenge in these environments since dateable material is often difficult to obtain, indicators such as mollusc shells may be reworked, and optically stimulated thermoluminescence (OSL) ages are susceptible to uncertainties related to weathering processes (eg, Federici and Pappalardo, 2006).

In the Mediterranean, similar challenges are associated with reliably dating erosional features such as wave-cut notches. In a recent study, Antonioli *et al*. (2006a) re-evaluate a widespread double tidal notch associated with MIS 5e, which has previously been cited as evidence for multiple highstands. Careful analysis of notch morphology led these authors to suggest the notches may have formed as a couplet during a single highstand, reflecting the combined action of isostatic adjustment and tidal erosion. At present, however, existing age constraints are not sufficient to confirm this hypothesis.

2 Land-level changes

Where interglacial shorelines are extensive and well dated, they can prove particularly useful in determining long-term crustal movements and tectonic influences. Raised beach deposits several decimetres above modern sea level are found along the coastlines of France and southern Britain, and have attracted considerable interest, in part due to their association with Palaeolithic activity (eg, Bates *et al.*, 1997; 2003; Coutard *et al.*, 2006). These beaches, along with river terrace staircases, indicate long-term uplift during the Quaternary (Westaway *et al.*, 2006). This contrasts with Holocene peat-based sea-level reconstructions suggesting more recent subsidence (Shennan and Horton, 2002), and highlights the time-dependent nature of significant trends and processes.

In the Mediterranean, a number of recent studies have used a range of highstand indicators to test and refine the current understanding of tectonics along the Italian coast (Antonioli *et al.*, 2006a; 2006b; Ferranti *et al.*, 2006). Since a variety of indicators are used, each with a different precision, recent reviews have employed a 'quality index' as a measure of reliability (eg, Ferranti *et al.*, 2006; Federici and Pappalardo, 2006). These data are used to map differential crustal movements (eg, Ferranti *et al.*, 2006) and provide information on isostatic effects versus seismic/tectonic processes.

3 Holocene highstands

Models of glacio-isostatic adjustment (GIA) provide quantitative explanations for the

contrasting height and timing of Holocene highstands which result from processes such as equatorial syphoning and continental levering (Mitrovica and Milne, 2002). In the Indian Ocean this pattern is complex, with emergent mid-Holocene (and last Interglacial) shorelines evident along many central and eastern coasts, but generally absent in the west (Camoin *et al*., 2004; Woodroffe, 2005). Many atolls, such as the Maldives, appear to indicate longer-term submergence (Woodroffe, 2005), although delimiting subtle changes during the late Holocene requires careful analysis of precise indicators. For example, Morner *et al*. (2004) suggest the Maldives register several highstands during the last 4000 years. These interpretations have been criticized by Kench *et al*. (2005b), Woodworth (2005) and Woodroffe (2005), who contend that the authors have misinterpreted data, fail to adequately account for vertical uncertainties associated with them, and invoke mechanisms for change that are implausible and unsupported by evidence.

Understanding recent changes in RSL is of critical importance in light of the often-cited vulnerability of low-lying islands (eg, Patel, 2006). The rate of sea-level change will affect the capacity of a reef to 'catch up', 'keep up' or ultimately, 'give up' (Kennedy and Woodroffe, 2002). In many areas like the Indian Ocean, determining rates of RSL change is hampered by the scarcity and limited duration of tide gauge records. Flat-topped coral microatolls, which form close to low tide level, have the potential to provide detailed records of RSL change that may complement and extend the sparse instrumental records from these regions (Smithers and Woodroffe, 2000; 2001). However, sea level is only one of a number of variables that influence coral-reef development. Other important parameters include nutrient supply, hydrodynamic conditions and substrate availability (Montaggioni, 2005). In fact, Kench *et al*. (2005a) have recently proposed a new model of reef-island evolution, based on a study in the Maldives, that suggests sea-level

rise may actually reactivate processes responsible for island accumulation. If this is correct, these and other islands may well be better equipped to deal with future sea-level rise than previously thought.

III Ice and ocean changes

At the end of the last glacial period, melting ice sheets released vast volumes of meltwater into the ocean. The classic, coral-based sea-level graphs from Barbados (Fairbanks, 1989; Bard *et al*., 1990), the Huon Peninsula (Chappell and Polach, 1991; Cutler *et al*., 2003) and Tahiti (Bard *et al*., 1996) chart the resulting sea-level rise from a lowstand of -120 ± 5 m at the last glacial maximum. These benchmark publications have been added to by sediment-based studies from the Bonaparte Gulf (Yokoyama *et al*., 2000) and Sunda Shelf (Hanebuth *et al*., 2000). The resulting picture is of deglacial sea level rising at an average rate of 10 mm/yr, but punctuated by major pulses of meltwater, contributing estimated volumes of water equivalent to melting between 1.5 and 3 Greenland Ice Sheets in only a few centuries (Alley *et al*., 2005). The number, timing and source of these meltwater pulses is still subject to debate, as is the amount of sea-level rise that has taken place since the final demise of the Laurentide ice sheet *c*. 6500 years ago.

1 Meltwater pulses

While the existence of a meltwater pulse around 14.5 ka BP (MWP 1a) is generally accepted, the source of this water is not (see Edwards, 2005). Bassett *et al*. (2005) continue the debate by examining discrepancies between several deglacial sea-level records. They argue these reflect the spatial fingerprint of a large (~15 m eustatic equivalent) Antarctic contribution to MWP 1a, rather than errors associated with the sea-level data (eg, Peltier, 2002). In a contrasting approach, Tarasov and Peltier (2005) examine the contribution of the North American Ice Sheet to MWP-1a by simulating its drainage chronology using an ensemble of glacial systems

models (calibrated in part by RSL data). Their results indicate that, while much of the meltwater associated with MWP-1a entered via the Gulf of Mexico, discharge into the Arctic Ocean peaked later during the onset of the Younger Dryas. Comparison with palaeoceanographic data leads Tarazov and Peltier (2005) to speculate that this freshwater flux may have affected the meridional overturning circulation and triggered the subsequent cold reversal.

Later pulses in sea-level rise have been proposed (eg, Fairbanks, 1989; Blanchon and Shaw, 1995) and tentative associations made with coastal records of change, such as the extensive raised shorelines of Scotland (eg, Smith, 2005). The existence of these events remains controversial, however, due largely to limitations associated with the sea-level data. This is illustrated by the recent debate relating to a paper by Toscano and Macintyre (2003) in which the authors propose a (smooth) sea-level curve for the last 11 000 years, delimited by dated samples of coral and intertidal mangrove peat. The ensuing discussion, which has appeared in press over the last few months, highlights, among other things: the care needed when using the classic reef-crest species *Acropora palmata* as a sea-level indicator; limitations associated with calibration of dates; the difficulties of objective data interpolation; and the potentially misleading picture derived by combining data across large areas with contrasting isostatic and tectonic signatures (Blanchon, 2005; Toscano and Macintyre, 2005; 2006; Gischler, 2006). It is important that these difficulties are resolved if we are to gain a clear picture of the manner in which long-term ice-sheet wasting proceeds.

2 Mid- to late-Holocene sea-level rise
The extent to which globally averaged sea levels have risen over the last 6000 years remains unclear. Field data are often interpreted on the basis of no significant meltwater addition during this interval, while many GIA models include a few metres of eustatic rise post 6000 BP (eg, 3 m, Lambeck, 2002). Modelling studies suggest that the Mediterranean region has the potential to constrain this addition since, at certain locations and time periods, RSL data can provide a relatively direct measure of the equivalent sea-level function (Lambeck and Purcell, 2005).

Mid-Holocene highstands are relatively rare in the Mediterranean as a whole, but Morhange and Pirazzoli (2005) identify evidence for RSL at +2 m along the southern coast of Tunisia. They argue that these and other Mediterranean field data do not match the results of existing geophysical models (eg, Lambeck and Bard, 2000; Lambeck *et al.*, 2004), and are incompatible with the suggestion of significant eustatic sea-level rise after 6000 BP (Pirazzoli, 2005; Morhange and Pirazzoli, 2005). Interestingly, in a paper that appears alongside that of Pirazzoli (2005), Lambeck and Purcell (2005) present updated GIA predictions for the Mediterranean. Their analysis predicts highstands should be found along the Tunisian coast, and that strong spatial gradients of around 4 m exist in this area. Clearly, as Pirazzoli (2005) concludes, increased collaboration between modellers and field scientists in this region has great potential.

3 Instrumental changes
In a previous progress report, Woodroffe (1994) highlighted the uncertainties surrounding the relationships among climate change (warming), ice-sheet response (mass balance) and sea-level rise, noting that future satellite observations should provide valuable insights into recent changes. Around a decade of such data are now available, and recent results indicate considerable temporal and spatial variability in both hemispheres.

Satellite altimeter data show that portions of the interiors of the Greenland and Antarctic ice sheets thickened between 1992 and 2003 (Johannessen *et al.*, 2005; Davis *et al.*, 2005). In the case of Antarctica, this is estimated to have reduced the rate of sea-level rise by 0.12 ± 0.02 mm/yr (Davis *et al.*, 2005). However, these data are poorly suited

to accurately resolving changes in areas with steep slopes such as ice-sheet margins and critical areas like the Antarctic Peninsula (Vaughan, 2005). Measurements of the Earth's gravity field provided by GRACE suggest that the Antarctic ice sheet as a whole actually lost mass equivalent to 0.4 ± 0.2 mm/yr sea level between 2002 and 2005, with most of this coming from the Western Antarctic Ice Sheet (Velicogna and Wahr, 2006). At present, mass estimates for the Eastern Antarctic Ice Sheet are associated with very large errors, with postglacial rebound the largest contributor to this uncertainty. Ongoing GIA modelling, validated by sea-level data, will help to reduce this uncertainty and improve mass-balance estimates.

Alternative observational data provided by radar interferometry suggests that, while the interior of the Greenland ice sheet is in approximate mass balance, there is rapid thinning around the periphery close to certain outlet glaciers (Rignot and Kanagaratnam, 2006). Many of these glaciers have accelerated, increasing Greenland's estimated contribution to sea-level rise from 0.23 ± 0.08 mm/yr in 1996 to 0.57 ± 0.1 mm/yr in 2005. This acceleration is also recorded by increased glacial seismicity (Ekström *et al*., 2006). Interestingly, these data are strongly seasonal, with seismicity increasing nearly fivefold during the summer months. This may indicate accelerations are linked to bed lubrication by increased meltwater penetration, suggesting that even modest changes in temperature ($\sim 1°C$) can produce large changes in discharge (Zwally *et al*., 2002; Joughin, 2006).

Satellite altimeter data are also being used in conjunction with tide gauge records to examine sea-level change during the last century (eg, Church *et al*., 2004). The advantage of this composite approach is that the spatial variability of sea-level rise, which is well represented by satellite data, can be 'grafted' onto the longer tide-gauge records, thereby providing a framework within which longer-term 'global mean sea level' trends can be identified. Church and White (2006) use this approach to extract a subtle acceleration in the rate of sea-level rise during the twentieth century that was previously undetectable using tide-gauge records alone. Similarly, Church *et al*. (2006) demonstrate that, while tropical Pacific and Indian Ocean sea levels show pronounced spatial variability related to the El Niño Southern Oscillation, sea levels in the region have been rising over the last 50 years.

IV Discussion

In the nineteenth century, Roman pillars standing in the marketplace at Pozzouli (Italy) featured in the debate between the catastrophists and uniformitarians. The issue at stake was the way in which the natural environment changes. Interest in these pillars stemmed not from their architecture, but rather from the fact that borings made by the marine bivalve *Lithophaga* riddled their surface up to 7 m above present sea level. Clearly the sea and/or land level had changed more than once since the marketplace was constructed. Less clear was when or how these changes had taken place.

Modern geological thinking acknowledges both progressive and punctuated change, but distinguishing one from the other still remains a challenge. An important ingredient in discriminating abrupt versus gradual sea-level change is the ability to tightly constrain age and altitude. For example, Morhange *et al*. (2006) returned to the pillars at Pozzouli to radiocarbon date *Lithophaga* still in their burrows which, along with other *in-situ* marine organisms, can fix 'biological sea level' to ± 5 cm (Morhange *et al*., 2001). These data showed that the columns recorded not one but three separate sea-level highstands between the fifth and fifteenth centuries, related to changes in the underlying Phlegrean Fields caldera.

The Pozzouli pillars neatly illustrate the truism that increased record detail tends to reveal greater record variability. While at vastly differing scales, similar relative increases in record detail and variability are apparent in many of

the sea-level and ice-sheet studies outlined above. This variability poses new challenges to existing conceptual and mathematical models of how sea-level/cryosphere/climate linkages operate during warm intervals, both at the suborbital (millennial) and subdecadal timescales. For example, the recent changes in Greenland revealed by seismic and satellite data cannot be explained by melting mechanisms alone (Rignot and Kanagaratnam, 2006). The physical processes associated with dynamic glacier change, perhaps linked to ocean warming and the retreat of tidewater glaciers (Joughin *et al*., 2004; Alley *et al*., 2005; Payne *et al*., 2004; Bindschadler, 2006), are not included in the current models used to predict future sea-level contributions (Marshall, 2005). Consequently, these models do not display the sensitivity to change indicated by recent remote sensing data and may underestimate the magnitude of future sea-level rise (Dowdeswell, 2006; Rignot and Kanagaratnam, 2006; Velicogna and Wahr, 2006). This is particularly interesting in light of a recent modelling study that proposes existing contributions from mountain glaciers and ice caps may have been overestimated (Raper and Braithwaite, 2006).

At the same time, the very variability that these recent studies have revealed is the reason why short-term records, no matter how detailed, are so poorly suited to providing projections of future change. To use a simple analogy, they are measures of weather rather than climate. In fact, in some instances, this is not far from the truth. For example, the recent precipitation-driven thickening of the Greenland ice sheet is apparently linked to the negative phase of the North Atlantic Oscillation (NAO) which dominated during the period of observation (Johannessen *et al*., 2005). This is in direct contrast to previous decades, and future predictions suggest the NAO will become increasingly positive as climate warms (Osborn, 2004; Kuzmina *et al*., 2005), reversing this thickening trend. For these kinds of reason, there is now some discussion as to whether the late Holocene in

general, and instrumental data in particular, are the most appropriate basis from which to infer future change (Henderson, 2005; Kennedy and Hanson, 2006).

An alternative is to examine records from previous interglacials, which provide a longer-term context against which more recent changes can be assessed. The last interglacial (LIG) has attracted particular attention as Arctic temperatures were warmer, sea levels higher and the Greenland Ice sheet smaller than present. For example, Overpeck *et al*. (2006) use a coupled ocean-atmosphere climate model to simulate LIG climate and compare this with simulations of the next 140 years to examine potential ice-sheet contributions to sea-level rise. Their results suggest that by 2100 the Greenland region will be at least as warm as it was during the LIG and, by implication, warm enough to melt large portions of the Greenland Ice Sheet. Similar results are suggested by Otto-Bliesner *et al*. (2006) who use a global climate model, a dynamic ice sheet model and palaeoclimate data to evaluate LIG Arctic warming. Their data suggest that retreat of the Greenland Ice sheet and surrounding icefields can contribute 2.2–3.4 m of sea-level rise over 2000–3000 years.

The question of whether recent ice-sheet changes are the first indications of possible future trends cannot be resolved with existing data. However, a study of marine sediments in Antarctica suggests that the recent breakup of a portion of the Larsen Ice Shelf is unprecedented in the context of the Holocene (Domack *et al*., 2005). A possible cause is undermelting from warming ocean waters (Shephard *et al*., 2003), and new oceanographic data show signs that such recent warming has occurred (Barnett *et al*., 2005), although, critically, data coverage from high-latitude seas is relatively poor (Hegerl and Bindoff, 2005).

If nothing else, both instrumental and geological data reinforce the fact that cryospheric (and sea-level) change cannot be predicted from simple indices such as temperature, and

that past changes have sometimes happened abruptly (eg, Rinterknecht *et al*., 2006). They also highlight the inadequacy of representing future change as two-dimensional, despite the iconic nature of certain x-y plots. This 'deadening of environmental space' as Lane (2005) puts it, is something that must be addressed if predictions of future change are to be viewed with any degree of security. The combination of satellite and tide-gauge data is an example of one of the ways in which this may be achieved (Church and White, 2006). In 2007, the IPCC fourth assessment report on climate change will summarize the latest consensus on conditions past, present and future. These will provide the basis for further testing and refinement in the light of new and enlarged data sets. Geographers, with their expertise in dealing with issues of scale, and change in four dimensions, are ideally situated to make a valuable contribution to this process (Maslin and des Clers, 2005).

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