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Sea levels: resolution and uncertainty

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I Introduction

This year saw the publication of two major works in the fields of climate and environmental change. The first, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), provides the latest scientific consensus regarding sea-level changes in the recent past and near future (IPCC, 2007). The second, the *Encyclopedia of Quaternary science* (Elias, 2007), is probably the most significant collective work on Quaternary science to date (Piotrowski, 2007). It contains several chapters relating to longer-term sea-level changes (10^2–10^5 years), the sources of data used to reconstruct them, and some of the important controlling variables (Cooper, 2007; Edwards, 2007; Gehrels, 2007; Horton, 2007; Milne and Shennan, 2007; Murray-Wallace, 2007a; 2007b; Nelson, 2007; Ó'Cofaigh and Bentley, 2007; Pirazzoli, 2007; Shennan, 2007; Woodroffe, 2007; Zong, 2007). The AR4 notes that this longer-term perspective is essential to assess the significance of recent changes and the processes involved (Jansen *et al.*, 2007). This report briefly reviews the AR4 sea-level summary and projections for future change. It then considers the development of high-resolution records of relative sea-level (RSL) change which have the potential to bridge the gap between instrumental data and longer geologically based reconstructions.

II The IPCC Fourth Assessment Report (AR4)

The AR4 concludes, on the basis of tide gauge records and satellite altimetry, that sea levels rose at an average rate of 1.7 ± 0.5 mm yr^{-1} during the twentieth century (Bindoff *et al.*, 2007). It also estimates future sea-level rise of between 0.18 and 0.59 m for the twenty-first century (Meehl *et al.*, 2007), derived from models driven by a series of 'Emission Scenarios' (Nakicenovic and Swart, 2000). These simple figures conceal substantial spatial and temporal variability (Church *et al.*, 2006; Nerem *et al.*, 2006; Beckley *et al.*, 2007), and progress in quantifying these represents an important advance in understanding since the IPCC Third Assessment Report (TAR) (IPCC, 2001).

Satellite data in particular emphasize the non-uniform nature of recent sea-level change, with some regions experiencing rates of rise up to five times the global average (eg, parts of the western Pacific Ocean), while elsewhere sea level is falling (eg, portions of the Indian Ocean). Projections of future sea-level rise are also spatially variable, reflecting

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in large part the importance of thermal expansion. This term, which contributes up to three-quarters of the projected sea-level rise by 2100, is calculated from combined atmosphere-ocean general circulation models. While the detailed geographical patterns of sea-level rise vary between models (and from those measured by satellites), some areas appear more likely to experience larger than average rises, reflecting changes in the fluxes of heat, freshwater and momentum between atmosphere and ocean (eg, Banks *et al.*, 2002; Suzuki *et al.*, 2005; Lowe and Gregory, 2006; Landerer *et al.*, 2007).

The AR4 also captures changes in the rate of sea-level rise through time when compared to the twentieth-century average. Hence, while the average rate between 1961 and 2003 was only slightly greater (1.8 ± 0.5 mm yr^{-1}), this increased to 3.1 ± 0.7 mm yr^{-1} for the shorter, more recent period (1993–2003). During this time, when improved observational data are available, the sea-level budget is more or less in balance (ie, the sum of the contributions equals the observed rate of change). For the earlier interval, however, the sum of the contributions totals 1.1 ± 0.5 mm yr^{-1}, and the AR4 concludes that this significant difference means that the budget is not 'satisfactorily closed' for this period. This highlights remaining gaps in our understanding of the various factors contributing to sea-level change, and/or the quality of our instrumental measurements.

Potentially one of the most significant gaps in current understanding centres on the role of ice sheet dynamics in contributing to sea-level rise, and stems from the growing instrumental evidence for such dynamism (see Edwards, 2006). This has required a re-evaluation of the timescales over which ice sheets may respond to climate change, and poses new challenges for ice sheet modellers (Howat *et al.*, 2007; Truffer and Fahnestock, 2007; Vaughan and Arthern, 2007). Since the current generation of continental ice sheet models used in the AR4 does not fully capture this dynamism, a scenario independent term (0.32 ± 0.35 mm yr^{-1}) is added to the predicted contributions from Greenland and Antarctica. This is derived from the portion of the present ice sheet mass balance estimated to be due to dynamic changes during the period 1993–2003 (namely all of the Antarctic contribution and half of the Greenland contribution). This approach inherently assumes the 1993–2003 contributions will remain unchanged in the future, but the AR4 notes that these may increase or decrease and that at present there is no way of assessing the likelihood of these alternatives.

Inevitably, general interest will tend to focus on the estimated range of future sea-level rise (0.18–0.59 m), and this range will be compared to the TAR projections of 0.09–0.88 m (IPCC, 2001), and the Second Assessment Report (SAR) values of 0.13–0.94 m (IPCC, 1996). Unfortunately, this may give the false impression that the magnitude of future sea-level rise has been revised down as our knowledge has improved. In reality, these numbers cannot be directly compared since they refer to subtly different time periods and are quoted with different confidence intervals. Importantly, the AR4 explicitly states that the midpoints of its projections are within 10% of those in the TAR when data are treated in the same way. Of greater significance, however, is the fact that the TAR upper estimate includes a measure of mass balance and ice dynamic uncertainty (equal to 10% of the mass loss from Greenland), while the AR4 considers the uncertainties associated with ice sheet dynamism too great to be rigorously assessed or integrated into models. Hence, a couple of decimetres may be added to the upper range of some scenarios if, for example, the imbalance presumed to be associated with recent climate change scales up with global average temperature rise (Meehl *et al.*, 2007). Catastrophic sea-level rise, for example due to failure of the Western Antarctic Ice Sheet, is still thought to be unlikely, however, with new evidence indicating sediment wedges at grounding lines may act to stabilize ice streams (Anderson, 2007; Alley *et al*., 2007; Anandakrishnan *et al*., 2007).

The complexity of dealing with these uncertainties led Rahmstorf (2007) to adopt a contrasting approach to projecting future sea-level rise. This employs a simple semi-empirical model based on the relationship between global sea level (derived from Church and White, 2006) and temperature (derived from Hansen *et al*., 2001) for the period 1880–2001. When driven by future warming scenarios of 1.4–5.8°C, the model simulates 0.5–1.4 m of sea-level rise between 1990 and 2100. In an alternative study, Rahmstorf *et al*. (2007) compare recent observations of global mean temperature and sea level with the TAR projections published in 2001. They observe that both increased at rates toward the upper limit of the projections.

These kinds of results, plus the inability to close the sea-level budget, and the tendency for AR4 models to underpredict instrumental sea-level rise, have led some to suggest that it would be prudent to regard the AR4 projections as conservative estimates (Kerr, 2007; Rahmstorf *et al*., 2007). Admittedly, there remains some uncertainty regarding the significance of the elevated rates of rise recorded between 1993 and 2003. Tide gauge data show that these rates are not unprecedented for a 10-year period, and so at present it is unclear whether they reflect decadal variability or an increase in the long-term trend. However, there are also questions surrounding the reliability of tide gauge estimates and the corrections applied to account for vertical land movements (eg, Holgate and Woodworth, 2004; Wöppelmann *et al*., 2006; 2007; Holgate, 2007). Longer-term sea-level records can provide a useful baseline against which this short-term variability can be assessed.

III High resolution sea-level reconstructions

In order to provide this longer-term perspective, the geological sea-level community faces the challenge of developing sea-level reconstructions with sufficient resolution and precision to permit meaningful comparison with instrumental records of change. In an earlier progress report, Edwards (2005) outlined several studies seeking to meet this challenge (Gehrels *et al*., 2002; 2005; Donnelly *et al*., 2004). This work continues with Gehrels *et al*. (2006) who reconstruct RSL changes since AD 100 from Iceland. These data, a portion of which are validated against a neighbouring tide gauge record, are of sufficient precision to examine centennial-scale RSL changes. The record shows an increase in the rate of RSL rise around AD 1800–1840, 50 years or so later than indicated in North America (Donnelly *et al*., 2004; Gehrels *et al*., 2005). The authors discuss the possible mechanisms responsible for the reconstructed changes with reference to a range of oceanographic data, highlighting the significance of both spatial and temporal variability. This type of discussion is only possible because of the precise nature of the reconstruction, which combines a detailed composite chronology (derived from AMS ^{14}C dating, tephra analysis, ^{210}Pb, ^{137}Cs, total Pb and Li concentrations, Pb isotopic ratios and palaeomagnetism), with a foraminiferal transfer function for tide level. Microfossil-based reconstructions such as this, which employ statistical techniques to quantify species-environment relationships, are becoming increasingly popular tools for those seeking to develop high-resolution records.

1 Microfossil-based reconstructions

Diatoms, foraminifera, pollen and testate amoebae have all been employed to reconstruct Holocene RSL change (Gehrels, 2007). The use of these sea-level proxies is based on several basic premises: the vertical distribution of microfossils is systematically related to RSL; these relationships can be quantified; both the microfossils contained within coastal sediments, and their relationship to former RSL, are time invariant; and that deposits/assemblages are in situ and faithfully reflect the altitude at which they formed. Each one of these premises is a focus of current research.

The vertical distribution of diatoms, foraminifera and testate amoebae can be directly linked to tide levels, and numerous studies continue to refine these relationships. While it has been common to focus on temperate environments (eg, Scott and Medioli, 1980; Patterson, 1990; Nelson and Kashima, 1993; Hemphill-Haley, 1996; Zong and Horton, 1999; Horton *et al*., 1999; Gehrels *et al*., 2001; Charman *et al*., 2002; Edwards *et al*., 2004; Szkornik *et al*., 2006), there is increasing interest in testing these techniques in tropical contexts (Barbosa *et al*., 2005; Horton *et al*., 2005; Woodroffe *et al*., 2005; Horton *et al*., 2007). In contrast, pollen distributions cannot be directly linked to RSL, and have more commonly been employed as an age marker in sediments (eg, Long *et al*., 1999; Edwards, 2001; Gehrels *et al*., 2005). However, there are comparatively few studies of intertidal pollen distributions, and a couple of recent papers suggest that, for higher-elevation environments away from the influence of tidal channels and freshwater inputs, local pollen distributions are strongly controlled by proximity to vegetation source (Roe and van de Plassche, 2005; Engelhart *et al*., 2007). Since vegetation is often vertically zoned, it may therefore be possible to use pollen as a sea-level indicator where other microfossils are not preserved, and existing sea-level indicators have large vertical uncertainties (Engelhart *et al*., 2007).

Several of the studies referred to above use transfer functions to quantify the relationship between the microfossil proxy and tide level, enabling the latter to be expressed as a function of the former. While early transfer functions used foraminifera from temperate salt marshes (Guilbault *et al*., 1996; Horton *et al*., 1999; 2000; Gehrels, 2000), recent studies have examined their application in mangrove systems in Sulawesi (Indonesia) and the Great Barrier Reef (Australia) (Horton *et al*., 2005; Woodroffe *et al*., 2005). Similar transfer function studies employing diatoms also indicate their potential use in sea-level reconstructions for temperate and tropical environments (Zong and Horton, 1999; Gehrels *et al*., 2001; Sawai *et al*., 2004; Horton *et al*., 2006; 2007; Szkornik *et al*., 2006). Composite microfossil studies have been suggested to provide improved reliability and precision although at the cost of additional analysis (Gehrels *et al*., 2001). For example, in a recent multiproxy study from British Columbia, Patterson *et al*. (2005) show that, while diatom, foraminifera and macrophyte assemblages all show statistically significant relationships with RSL, the strongest relationship of all is developed when all three proxies are considered in concert. If selecting only one microfossil group, Patterson *et al*. (2005) recommend foraminifera for ease of sample preparation and analysis.

Horton and Edwards (2006) present a detailed synthesis of foraminifera-based transfer functions and their application to sea-level reconstruction. They list several strengths of the transfer function approach, including the fact that reconstructions have quantified error terms, and that the transparent, replicable methodology can assist in record comparison and correlation. However, they argue against using transfer functions as ‘black boxes’, emphasizing the need to understand foraminiferal ecology and taphonomy. For example, there is still considerable disagreement concerning the significance of infaunal foraminifera and their potential influence on sea-level reconstruction (eg, Ozarko *et al*., 1997; Culver and Horton, 2005; Duchemin *et al*., 2005; Tobin *et al*., 2005; Horton and Edwards, 2006). Furthermore, they emphasize that transfer function error terms are a measure of precision not accuracy, and that complementary methods are required to assess the validity of any resulting reconstruction.

Training set qualities, and the choice of statistical method used, can have important impacts on the performance of the resulting transfer function, and its susceptibility to problems such as spatial autocorrelation (eg, Telford and Birks, 2005). Horton and Edwards (2005; 2006) demonstrate that, while foraminiferal training sets constructed from site-specific data sets are often more precise (smaller vertical error terms), they can result in less accurate reconstructions due to the fact that the best modern analogue for past environmental conditions may be located some distance from the study site. However, problems can arise when comparing assemblages from areas in which additional variables, such as salinity, exert contrasting influences on microfossil distributions (eg, Culver and Horton, 2005; Horton and Murray, 2007). Similarly, seasonal effects mean that species-environment relationships can be influenced by the time of sampling, and training sets based on one-off sample collection will tend to overestimate vertical precision (Horton and Edwards, 2003; Horton and Murray, 2006).

There is still considerable scope for improving measures of transfer function accuracy, and establishing the environmental limits beyond which reconstructions become unreliable. Detailed lithostratigraphic analysis is essential for providing the context into which reconstructions derived from microfossil analysis of selected cores can be placed. For example, proximity to tidal creeks and channels can have important impacts on some of the microfossils outlined above. While, in some instances, channel deposits are evident in the field and clearly distinguished by changes in microfossil assemblage (eg, Evans *et al*., 2001; Evans and Kirby, 2002), this is not the case in all areas (eg, Allen *et al*., 2006). More sophisticated laboratory analysis of textural and geochemical signatures contained within sediments has the potential to provide important information to complement the results of microfossil studies.

2 Sedimentary and geochemical indicators

Rapidly accumulating sediments can provide extremely high-resolution records of change. For example, Allen and Haslett (2006) use foraminifera and pollen data in combination with grain size analysis to investigate coastal and sea-level changes in the Severn estuary, UK. They report centimetre- to decimetre-scale annual banding, which is expressed texturally (resulting from seasonal changes in windiness and water temperature effects on viscosity) and palynologically (reflecting flowering and sporulation patterns). Allen *et al*. (2007) go on to analyse these sediments geochemically, in an attempt to extract seasonal signals in $\partial^{13}C$ and C/N ratios, reflecting the fact that particulate organic carbon (POC) is sensitive to seasonal changes in the proportions of C3 and C4 vegetation within a catchment (Weiguo *et al*., 2003). These studies reveal that portions of the sequences accumulated at extremely rapid rates (up to 25 mm yr^{-1}), an order of magnitude greater than the long-term average for a given bed.

Isotopic/geochemical data have been used to investigate the possibility of extracting a RSL signal directly from intertidal sediments (Wilson *et al*., 2005a; 2005b). This approach is based on the idea that terrestrial vegetation and tidally derived POC are the two main sources of carbon to the surface of salt marshes, and that they have distinctive $\partial^{13}C$ and C/N ratios. This results in an abrupt change in surface sediment $\partial^{13}C$ at the upper tidal limit, and more gradual changes within the intertidal zone reflecting the frequency and duration of flooding. Initial results from sediment cores suggest that this general relationship is preserved in Holocene sediments, and produces qualitative results that are comparable to microfossil-based reconstructions (Lamb *et al*., 2007). Decomposition can induce changes in $\partial^{13}C$ and C/N ratios that may be confused with switches in carbon source, and care must be taken in the storage of sediment cores to minimize similar processes after collection (Lamb *et al*., 2006; 2007). Nevertheless, these data provide a useful complement to microfossil-based reconstructions since they are influenced by different controlling variables. In particular, they can identify changes occurring within a catchment that may influence the intertidal environments located within an estuary, and the RSL records derived from them (Lamb *et al*., 2007).

In the organic-rich saltmarshes of North America, C3 and C4 plants occupying different marsh elevation zones are preserved within the sedimentary sequences. While allochthonous organic matter complicates the simple interpretation of isotopic signatures (McMahon *et al*., 2005), Tanner *et al*. (2007) and Johnson *et al*. (2007) attempt to circumvent this by using compound specific isotopic analysis of lipid biomarkers. Both studies demonstrate the potential for detecting shifts in salt marsh plant communities, but Tanner *et al*. (2007) suggest that these kinds of data will still need to be combined with other proxies for sea level, such as foraminifera, in order that the influence of other controlling variables (eg, salinity) can be accounted for.

3 *Discussion*

'High-resolution' is a relative term, dependent upon the relationships among precision, sampling interval, and the scale of change under investigation. Precise microfossil-based reconstructions and rapidly accumulating sedimentary environments go some way toward facilitating the development of records that may be compared with instrumental data. However, increasing record resolution is not simply a matter of finding locations with higher sedimentation rates, developing transfer functions with smaller vertical errors, or sampling at increasingly fine intervals. As the timescale of investigation changes it is also necessary to re-evaluate the appropriateness of the methodologies employed, and the validity of the assumptions that underpin them.

Constructing a reliable chronology becomes a major challenge when moving from multicentennial- to decadal-scale studies. Sediment-rich systems with high accumulation rates have the potential to furnish extremely detailed records, but these are commonly the most stratigraphically incomplete, reflecting the episodic nature of deposition, erosion and transport in shallow marine environments (Sommerfield, 2006). For example, while laminated sediments can provide information on changes occurring over tidal cycles, sedimentation rates and layer preservation are highly variable in time (eg, Long *et al*., 2006; Frouin *et al*., 2006; Deloffre *et al*., 2007). Hence, while records have extremely high-resolution segments, they are discontinuous in nature at these timescales. Studies employing sea-level index points have not needed to consider this, since the methodology employs discrete, individually dated points to provide 'snapshots' of former RSL position. In contrast, sediment core chronologies are commonly derived by interpolation between dated horizons, with the ages of microfossil-based reconstructions inferred from the resultant accumulation histories. Horton and Edwards (2006) illustrate how undetected rate changes, or breaks in sedimentation, will distort the resulting RSL curves.

In many cases, hiatuses are extremely difficult to detect (Weedon, 2003). For example, while major erosional breaks extend over several kilometres of the Caldicot Levels (UK), these are often subtly expressed in the stratigraphy and only apparent after laboratory analysis of sediment grain size (Allen and Haslett, 2002; 2006). Similar cryptic hiatuses are noted by van de Plassche *et al*. (2006) in Connecticut (USA), where detailed lithostratigraphic investigation and dating revealed a 900-year erosive hiatus extending throughout the salt marsh system. It is therefore important to improve the resolution of core chronologies in tandem with increases in the detail of microfossil-based reconstructions (eg, Gehrels *et al*., 2006). The combination of data from multiple cores, and careful examination of individual records for abrupt changes, can improve resulting chronologies and help to identify hiatuses (Edwards and Horton, 2006; Horton and Edwards, 2006).

The presence of hiatuses has a more subtle influence when attempting to link longer-term records employing radiocarbon dating with shorter-term chronologies derived from radionuclides such as ^{210}Pb. In shallow-marine contexts, accumulation rates tend to scale inversely with the timespan under consideration, and stratigraphic completeness for a given sediment column will vary depending on the temporal resolution at which it is examined (Sadler, 1999; Sommerfield, 2006). Sommerfield (2006) notes that this is particularly problematic when attempting to link ^{210}Pb and ^{14}C data together since this commonly requires extrapolation of accumulation rates to produce a seamless composite chronology. The end result can be an apparent increase in the rate of sedimentation, driven primarily by differences in stratigraphic completeness. This is particularly important to consider when attempting to link geological and instrumental records together, since in many instances the microfossil reconstructions indicate minimal change in sediment elevation, and increases in the rate of RSL are essentially driven by increased sedimentation rate (eg, Gehrels *et al*., 2002; 2006).

While salt marshes may experience long-term accumulation rates that approximately track RSL, this relationship becomes increasingly complex as the temporal resolution of the study increases (French, 2006). For example, in microtidal areas, such as the Danish Wadden Sea, Bartholdy *et al*. (2004) suggest short-term variations in sedimentation are strongly influenced by atmospheric circulation, while French (2006) highlights the potential significance of the lunar nodal cycle in producing interdecadal differences in sedimentation rate. These are examples of scale-dependence, where records are examined at increasingly fine resolutions, the nature of the processes and variables being measured changes.

This scale-dependence is also a significant consideration for sea-level proxies seeking to produce 'high-resolution' pictures of change over much longer (glacial–interglacial) intervals. For example, while marine oxygen isotope data underpin our understanding of orbital-scale sea-level changes, their interpretation is based upon the tenet of spatial and temporal consistency, which breaks down if the records are examined at millennial timescales (Skinner and Shackleton, 2006). The difficulties of extracting a 'sea-level' equivalent from what are effectively parochial isotopic signatures are compounded by the fact that coral reef data, which are often used to constrain the inferred variations, respond poorly to rapid sea-level changes (Hearty *et al*., 2007). In addition, ecological time-averaging in coral reefs means that single dates from horizons may be significantly in error, and consequently records derived from cores may only be accurate at millennial scales or greater (Edinger *et al*., 2007). Hence, while some studies claim centennial- to millennial-scale resolution on the basis of sampling (eg, Siddall *et al*., 2003; 2006; Rohling *et al*., 2004), accurately interpreting results is not straightforward, and limitations in chronology can result in erroneous phase relations (Skinner and Shackleton, 2006; Arz *et al*., 2007).

IV Conclusion

Scientific uncertainty, as represented by ranges of values and error terms, does not immediately translate into measures of confidence or validity. The AR4 projections of sea-level rise do not represent the true range of possible futures due to fundamental gaps in underlying knowledge. Similarly, the vertical error terms associated with microfossil-based RSL reconstructions, while much vaunted, represent only a portion of the underlying uncertainties, and provide no indication of ultimate accuracy. The treatment of chronological uncertainty is particularly limited, and the lack of an agreed methodology means that this is often ignored. Some recent studies have attempted to convey the errors associated with dating and establishing reliable age-depth relationships (eg, Gehrels *et al*., 2005; 2006; Edwards and Horton, 2006), but future studies will need to integrate further developments in quantifying and presenting chronological uncertainty (eg, Blaauw and Christen, 2005; Blaauw *et al*., 2007).

The climate change community has given explicit consideration to the ways in which scientific uncertainty is calculated, defined and communicated to the target audience (eg, Manning *et al*., 2004; Kandlikar *et al*., 2005; Patt and Dessai, 2005). Some of these approaches, such as the use of ranges derived from ensembles of model runs, comparison of model output with observation, and clearly stating associated assumptions and limitations, can usefully be integrated into the ongoing development of quantitative palaeoenvironmental reconstructions. While the drive towards higher-resolution records demands an increase in detail and a reduction in error-terms, it is important not to lose sight of what these terms really represent, or the scale-dependence of the methodologies employed and the underlying processes they seek to examine.

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