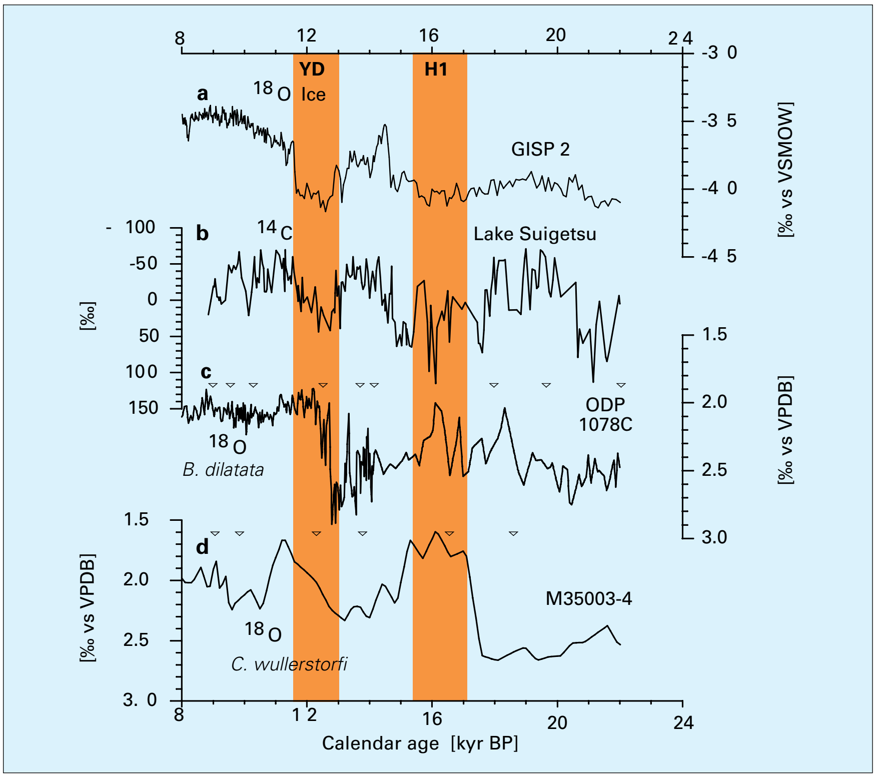

*Fig. 2: Comparison of oxygen isotope ratios of the benthic foraminifera B. dilatata (**c**) and C. wuellerstorfi (**d**) (Hüls, 2000) from sediment cores ODP 1078C (11°55' S, 13°24' E; 426 m water depth) and M35003-4 (12°05' N, 61°15' W; 1299 m water depth), respectively, indicating tropical Atlantic intermediate-depth temperatures, with (**a**) oxygen isotopes from the GISP2 ice core displaying air temperatures over Greenland, and (**b**) atmospheric radiocarbon from sediments of Lake Suigetsu, Japan (Kitagawa et al. 2000; adapted from Clark et al., 2002). ^{14}C AMS control points for ODP 1078C and M35003-4 are denoted by triangles above the respective record. H1 and YD denote Heinrich event H1and the Younger Dryas period, respectively. The record of $\Delta^{14}C_{atm}$ (**b**) is a function of the production rate of ^{14}C in the upper atmosphere and the sizes of and exchange rates between the major carbon reservoirs. North Atlantic Deep Water (NADW) is presently the major source of ^{14}C to the deep sea, and changes in the strength of this water mass probably dominate the variations in $\Delta^{14}C_{atm}$. Positive anomalies in the $\Delta^{14}C_{atm}$ record hence largely reflect reduction of NADW production and thermohaline overturning (Clark et al., 2002).*

present-day circulation with a weak North Atlantic freshwater flux of 0.03 Sv (1 Sv = 10^6 m^3 s^{-1}), we find that the observed mid-depth warming rate in the low-latitude Atlantic (Arbic and Owens, 2001) is consistent with a weakening of the THC by only 5-15% (not shown here).

In view of uncertain Atlantic overturning reduction, it is inevitable to design a proper strategy for the early detection of THC change. Intermediate-depth waters provide a potentially sensitive indicator of anthropogenic climate change related to the THC, which has shown to be one of the most uncertain processes of possible future climate shifts. A primary objective of several climate research programs is to design practical strategies for monitoring climate variability and THC changes. Using a novel combination of paleoceanographic records, climate modeling results and recent oceanographic evidence we highlight the importance to include long-term temperature measurements of the low latitude mid-depth Atlantic as an integrative indicator of THC change in such a monitoring system. We argue that the rates of temperature change of intermediate-depth waters at Heinrich event H1 and the Younger Dryas provide a benchmark against which to assess warming rates in the 20th century as well as in the future.

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Past Rates of Sea Level Change

Nick Harvey

University of Adelaide, South Australia, 5005, Australia; nick.harvey@adelaide .edu.au

Rates of sea level change identified from the geological record can be separated into longer-term (<1,000 ka), the post-glacial marine transgression (20 ka to 7 ka) and the subsequent adjustment to modern levels (>7 ka). In addition, there are historic rates from instrument measurements.

<1,000 ka

Long term geological rates of sea-level change provide a perspective on the cyclical nature of sea level and the extent to which current and predicted sea-level changes are perturbations from natural cycles. Oxygen isotope ($^{18}O/^{16}O$) ratios of planktonic foraminifera from deep-sea sediments provide evidence of sea level fluctuations over numerous glacial/interglacial cycles with the Vostok ice core providing additional detailed records for the last four cycles. An approximate 100 ka periodicity for these cycles has been identified in the geological record and correlated with the oxygen isotope record in southeast Australia where, a series of stranded dune barriers dating back to 800 ka is associated with at least 10 interglacial high stands of sea level. Geological evidence of the rate of sea-level change across an entire glacial-interglacial cycle is provided by the coral record from Barbados and the detailed record of coral terraces preserved on the rapidly uplifting coast of the Huon Peninsula in New Guinea.

20 ka to 7 ka

Some of the fastest rates of sea-level rise from the glacial/interglacial cycles are associated with the post-glacial periods of deglaciation and global warming, most recently following the last glacial maximum of 20 ka.

Detailed geological investigations reveal rapid rates, such as in the South Australian gulfs where a sea-level rise of 9 mm/yr has been estimated between 10-8 ka and a more rapid rate of 24 mm/yr (Fig. 1) between 8-6.7 ka (Belperio, 1995).

7 ka to Modern

Coastal adjustment to the post-glacial redistribution of water and ice and differential loading of the lithosphere has produced varying rates of sea-level change around the globe. Post glacial sea-level changes are still impacting on the coast in many parts of the world as demonstrated by local or regional glacio-isostatic movements in the northern hemisphere and the global pattern of hydro-isostatic coastal adjustment (Houghton et al, 2001; Peltier, 2001). This has produced a sea level fall over the last 6-7 ka for some locations such as for Port Pirie in South Australia where Harvey et al. (1999) use paleo sea level indicators to demonstrate a rate of fall of 0.33 mm/yr. Higher rates of sea-level fall occur away from the continental margin at Port Augusta and lower rates at Ceduna closer to the margin (see Fig. 1).

Elsewhere, the use of fixed biological indicators such as coral microatolls (Fig.2) and encrusting

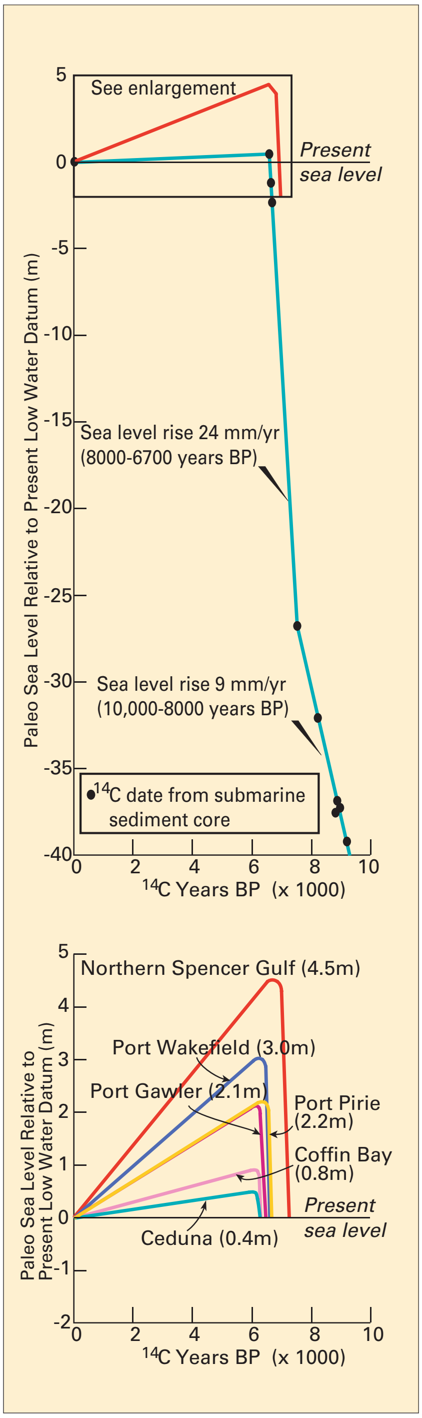

Fig. 1: Sea-level rates from South Australia following the postglacial maximum period and for the subsequent period of hydroisostatic shelf deformation (source: Harvey et al, 2002 after Belperio, 1995).

tubeworms provide high-resolution paleo sea-level datums from which palaeo sea level curves and rates can be derived and correlated with the geophysical models. However, there is debate over the method of deriving these rates and the use of smooth or oscillating sea-level curves (see Baker and Howarth, 2000).

Historic Records

Rates of change measured by tide gauges require geological correction but are becoming more refined with the use of satellite altimetry and geodetic measurements. The IPCC third assessment report (TAR) draws a number of conclusions from its analysis of global average sea level rise derived from tide gauge records (Houghton et al., 2001).

- First, very long tide gauge records suggest that the average rate of sea level rise was less in the 19th century than the 20th century.

- Second, tide gauge records for the 20th century give a mean sea-level rise in the range 1-2 mm/yr with a central value of 1.5 mm/yr.

- Third, although there is a decadal variability in extremes there is no widespread increase in extremes apart from that associated with a change in the mean (Houghton et al., 2001).

Methodical Remarks and Modern Rates

Tide gauge records measure only relative sea level so that it is important to have long-term reliable records, which are free of vertical crustal movements due to plate tectonics. These records need to be correctable for glacial rebound and should be either insensitive to small changes or be capable of editing based on oceanographic considerations (Douglas, 2001). Douglas selects 27 sites (with records exceeding 70 yrs) from around the globe to establish a 20th century global rate of sea level rise (Douglas, 2001). However, sites from the relatively stable Australian continent are excluded and Houghton et al. (2001) comment on the omission, given that the two longest records from Australia are both in excess of 80 years.

In order to obtain a clearer picture of mean sea-level trends it is important to correct the records for local and regional influences. For example, Harvey et al. (2002) demonstrate geologic, isostatic and anthropogenic influences on southern Australian tide-gauge records occurring at time scales of 106 yrs, 104 yrs, and 102 yrs, and rates of 0.07 mm/yr, 0.4 mm/yr and 2.0 mm/yr, respectively. Elsewhere, long-term tide gauge records have been adjusted for vertical land movements using either geological methods or post-glacial rebound models. The estimates provided by various authors were discussed in the TAR which noted that the wide range of rates reflects, in part, the different assumptions and methods used for estimating vertical land movement and also the different selection criteria for the tidal data used (Houghton et al., 2001).

Houghton et al. (2001) comment on different sea-level rise rates for the North American east coast where Peltier's rates (1.9 mm/yr) are significantly higher than those of both Gornitz (1.5 mm/yr) and Mitrovica and Davis (1.4 mm/yr) for the same region. Houghton et al also comment on the difference between lower European rates (1-1.1 mm/yr) relative to the higher North American rates (1.4-2.0 mm/yr). They suggest that this may reveal a real regional difference in sea level because of higher rates of sea level rise for the sub-tropical gyres of the North Atlantic in recent decades (Houghton et al., 2001, p. 661).

Australian data from two long-term sites, Sydney (82 yr record) and Fremantle (91 yr record) have been calculated by Houghton et al. (2001) using GIA corrections from the Australian-based rebound model of Lambeck and Nakada (1990), giving rates of 1.07 mm/yr and 1.55 mm/yr respectively. Sea-level rise rates from Southern Australia (Harvey et al., 2002) are significantly lower. These rates corrected using geological methods have been obtained for a number of sites with record lengths of up to 60 years, giving individual tide-gauge site rates of between 0.14 to 0.87 mm/yr. Thus, the far field data from the relatively stable Australian continent suggest sea-level rise rates lower than the central value of 1.5 mm/yr for global average sea-level rise adopted by Houghton et al. (2001) in the TAR.

Fig. 2: A microatoll from the south coast of Fiji showing both living coral and an elevated section related to a higher sea level. Such palaeo sea-level indicators are used to determine Holocene sea-level curves.

The most recent IPCC scientific assessment (Houghton et al., 2001) draws a number of conclusions on the factors affecting current rates of sea level change. Over the last century, ocean thermal expansion is estimated to have contributed between 0.3 to 0.7 mm/yr based on Atmosphere-Ocean General Circulation Models. The contribution from the melting of glaciers and ice caps is estimated to range from 0.2 to 0.4 mm/yr based on observational and modeling studies. Modeling studies also estimate the contribution from the Greenland ice sheet of 0.0 to 0.1 mm/yr and from the Antarctic ice sheet as -0.2 to 0.0 mm/yr. These figures result in a total estimate of eustatic sea level rise for the last century between -0.8 to 2.2 mm/yr producing a central value lower than expected from the observational records (Houghton et al., 2001).

Comparison of Past and Present Rates

It is clear that most recent post-glacial sea level transgression has produced rates of sea-level rise (>24 mm/yr) from prehistoric time well in excess of current rates (1-2 mm/yr). Although the rates for the 20th century appear faster than the rates for the 19th century it has been estimated that in order to reach the IPCC projected sea level (central value) by 2100, it would require a rate of sea level rise between 2.2 and 4.4 times the rate for the last century (Houghton et al., 2001).

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