**Climate
of the Past**

Sea level ~400 000 years ago (MIS 11): analogue for present and future sea-level?

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Abstract. Comparison of the sea-level today with that of 400 000 years ago (MIS 11), when the Earth's orbital characteristics were similar may provide, under conditions of natural variability, indications of future sea-level during the present interglacial. Then, as now, orbital eccentricity was low and precession dampened. Evidence for MIS 11 sea-level occurs on uplifting coastlines where shorelines with geochronological ages have been preserved. The sea-level term and the uplift term may be separated with an "uplift correction" formula. This discovers the original sea-level at which the now uplifted shoreline was fashioned. Estimates are based on average uplift rates of the "last interglacial" sea-level (MIS 5.5) using a range of estimates for sea-level and age at that time at different locations. These, with varying secular tectonic regimes in different ocean basins, provide a band of estimates for the MIS 11 sea-level. They do not support the hypothesis of an MIS 11 sea-level at ~20 m, and instead show that it was closer to its present level.

1 Introduction

Inferences about sea-level variability have been drawn from the oxygen isotope variability (δ^{18}O) of marine foraminifera ever since Emiliani (1955) proposed correlations between δ^{18}O and classical continental stratigraphy. This was extended by correlations between sea-levels, δ^{18}O and solar variability (Fairbridge, 1961). Whereas Emiliani (1955) placed greater emphasis on the temperature term rather than the isotopic composition of the ocean in the partitioning of ^{16}O and ^{18}O (δ^{18}O), Shackleton (1967) argued that the δ^{18}O signal from bottom water benthic foraminifera, where little

if any temperature change occurred, is a signal of ocean isotopic variability. Because this is controlled by continental ice-volume, it is also a signal of sea-level variability. Shackleton and Opdyke (1973) proposed that 0.1‰ of δ^{18}O change is equivalent to a 100 m of sea-level change: thus 0.01‰ corresponds with 10 m of sea-level change. Subsequently, it was realised that ocean bottom water temperatures did change in the past and regional hydrological variability is also a factor in the partitioning of the oxygen isotope signal (e.g. Lea et al., 2002). Many clever attempts have been made to convert δ^{18}O to its sea-level equivalent by Chappell (1974), Shackleton and Chappell (1986), Shackleton (1987), Waelbroeck et al. (2002), McManus et al. (2003), and Zeigler et al. (2003) believed that ocean core SITE 849 from the NE Pacific may provide a close approximation for sea-levels of the last 0.5 Ma (Mix et al., 1995). More recently, correlations have been made between oxygen isotope, temperature and carbon dioxide variability in Antarctic ice cores with sea-level (Rohling et al., 2009). But all such correlations with sea-level are based on inference of one kind or another.

The only reliable indicators of former sea-levels (water-levels) are geological actualities on the global shore and its immediate hinterland. Advances in geochronology beyond the range of radiocarbon dating have opened up possibilities to obtain ages for old shorelines. Most of these, however, have been uplifted above the present sea-level so that "uplift correction" is needed (see Sect. 2 below). Evidence for former sea-levels is provided by: marine terraces, shoreline angles, erosional and bioerosional notches, littoral and beach sediments, back-barrier deposits, fossil corals and other marine organisms that indicate past water levels. Others include a range of water levels: for example, corals grow up to mean low water mark and may show variability up to a 5 m water depth and with the rising sea-level some reefs are "keep up" (Barbados), "catch up" (Bermuda) or "give up" (Neumann

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and MacIntyre, 1985). The most reliable indicators of former sea-levels are shoreline angles, notches and back barrier deposits and are used in this analysis.

Estimates of the MIS 11 sea-level relative to present sea-level fall into two groups. First: below present sea-level to ∼6 m above it (Bender et al., 1979; Suggate, 1992; McManus et al., 1999; Vézina et al., 1999; Murray-Wallace, 2002; Bowen, 2003a; Schellmann and Radtke, 2004a, b; Thompson and Goldstein, 2005). Second: a higher group at ∼20 m a.s.l. (Pirrazoli et al., 1993; Howard, 1997; Hearty, 2002; Hearty et al., 1999; Olson and Hearty, 2009; Rohling et al., 1998). These compare with inferences of sea-level from $\delta^{18}O$ of a band of sea-levels between ∼0 m (McManus et al., 1999, 2003) and ∼6 m (Waelbroeck, 2002).

2 Method

Estimating MIS 11 sea-levels is based on an "uplift correction" procedure that calculates average (not constant) tectonic rates of uplift from uplifted and dated MIS 5.5 shorelines (Chappell, 1974). Such average uplift rates may then be extrapolated to dated MIS 11 shorelines. The "uplift correction" formula is based on Pillans et al. (1998):

$$S = H - Ut, \quad \text{with} \quad U = (H^* - S^*)/t^* \tag{1}$$

where S is sea-level at time t relative to present sea-level, H is the elevation of the marine deposit with age t, and where U is the average tectonic uplift rate at a location. U is calculated from the elevation H^* of a reference marine deposit of age t^*. H and H^* should ideally lie on, or close to, a transect normal to the present shoreline.

Relatively few age estimates are available for uplifted MIS 11 shorelines. Some locations have age estimates based on U-series, ESR, AAR and TL in certain environments (see Sect. 3.2). Time t, however, is taken as event MIS 11.3 (406 ka) on the Bassinot et al. (1994) timescale. It receives strong support from the $^{40}Ar/^{39}Ar$ ages of 416±11 and 407±11 on tephra within estuarine sediments in Lazio downstream from Rome (Karner and Marra, 2003). Time t^* (MIS 5.5) is used to calculate uplift rates for "uplift correction". But unfortunately there is no universal agreement on its precise age or the elevation of its sea-level, and ages range from ∼132 to 116 ka. These point to a longer interglacial than predicted by orbital theory (Muhs, 2002; Muhs and Szabo, 1994; Muhs et al., 2002; Stein et al., 1993). Thus, the global complexity of the climate system may have resulted in a long sea-level response during the last interglacial (Muhs et al., 2002), with different responses in earlier ones (Siddall et al., 2007). During the possible ∼16 kyrs of the last interglacial (MIS 5.5) some variability in sea-level occurred as, on one hand, inferred from $\delta^{18}O$ at site ODP 980 west of Ireland (McManus et al., 1999; Oppo et al., 2006), and on the other hand from detailed geomorphological mapping and ESR ages on reefs and terraces in Barbados (Schellmann
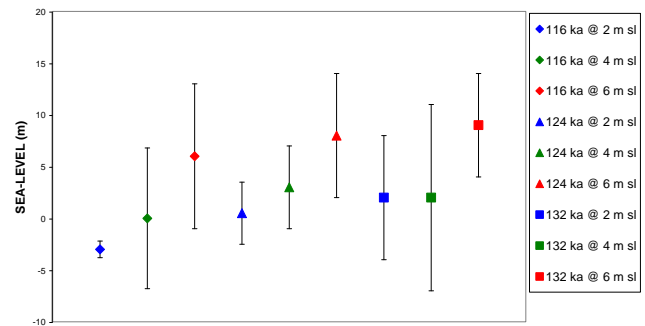
Fig. 1. MIS 11.3 sea-level and MIS 5.5 sea-level estimates for average uplift rates.

and Radtke, 2004a, b). It has been suggested that the highest MIS 5.5 sea-level occurred late and precipitously and was caused by a catastrophic collapse of the West Antarctic ice-sheet (Hollin, 1965; Neumann and Hearty, 1996; Hearty et al., 2007), but this has received little support (Carew, 1997; Mylroie, 1997).

The elevation of the last interglacial MIS 5.5 sea level (H^*) has been generally accepted as 6 m a.s.l. But a review of the literature by Murray-Wallace and Belperio (1991) concluded that: "the concept of a reference level of 6 m for the elevation of the MIS 5.5 sea-level is based on the observations of Veeh (1960) that fossil corals throughout the Pacific and Indian Oceans are found consistently between 2 m and 9 m. Broecker et al. (1968), Chappell (1974), Bloom et al. (1974) and many others have since used a 6 m reference as a de facto global eustatic sea-level for the last interglaciation". It was proposed that the coastline of the stable Gawler craton in South Australia was a better MIS 5.5 sea-level datum because its shoreline runs for ∼150 km at an elevation of 2 m (Murray-Wallace and Belperio, 1991). Similarly, a stable area of West Australia was proposed as an informal type area for the MIS 5.5 sea-level where TIMS ages of 128±1 to 116±1 on corals lie at about 3 m a.s.l. (Stirling et al., 1998). Since the review of Murray-Wallace and Belperio (1991) other locations have been discovered with an MIS 5.5 sea-level of 6 m. But all require evaluation of their tectonic history, and it seems unlikely that tectonic stability can be taken for granted anywhere.

Because of the range of ages and sea-level elevations for the MIS 5.5 sea-level in the literature, different ages and sea-levels are used to explore possible uplift rates and estimates of the MIS 11 sea-level (Tables 2, 3 and Fig. 1). Calculations based on the uplift rate of the MIS 5.5 sea-level at different locations (Table 1) are made with sea-level at 2 m, 4 m and 6 m for ages of 116 ka, 124 ka and 132 ka, which represent the earliest, latest, and median ages of MIS 5.5. Table 3 shows the results from which outliers, defined at, or greater than, two standard deviations, have been removed (Tables 2 and 3).

Table 1. Locations arranged in order of increasing uplift (example is MIS 5.5 sea-level of 2 m at 124 ka), evidence for MIS 5.5 and MIS 11 shorelines and tectonic style of locations.

Location	Uplift m/ka	MIS 5.5	MIS 11	Tectonic
Charleston S Carolina	0.05	back-barrier	back-barrier	Carolina Platform
Coorong CP Aust.	0.07	back-barrier	back-barrier	intra plate
Curacao, Antilles	0.07	coral platform	coral platform	island arc
Nome, Alaska	0.08	shoreline	shoreline	intra plate
Lazio, Italy	0.15	shoreline angle	estuarine	Extensional belt
Barbados	0.3	shoreline angle	shoreline angle	island arc
Sumba I, Indonesia	0.47	shoreline angle	shoreline angle	island arc

Table 2. MIS 11 sea-levels (S) calculated from different MIS 5.5 Ages and sea-levels for uplift correction (Table 3). Sea-level Calculations with removal of outliers (blank spaces) identified at or greater than two standard deviations. Numbers rounded-up.

Age ka	116			124			132			S
MIS 5.5 s–l	2	4	6	2	4	6	2	4	6	
Charleston	−5	3	7	−5	3	7	−5	3	7	2±5
Coorong CP	−2	6	14	0	6	14	2	6	14	7±6
Curacao	−3	5	13	3	5	13	1	9	13	7±6
Nome CP		−5	3		−1	3	−9	−1	3	−1±5
Lazio	−2	6		2		6				3±4
Barbados	−2	−2	−2	−2	−2	−2	6	10		0.5±5
Sumba I	−13	−13	−1	−1	7	11	11	−13		−1.5±11
S	−3	0	6	0.5	3	8	2	2	9	
	±1	±7	±7	±3	±4	±6	±6	±9	±5	

Viscoelastic Earth models have investigated glacio-hydro-isostatic processes that caused spatial and temporal variability in sea-level for Termination 1 at the MIS 2/1 transition (e.g. Peltier, 2004), and Termination 2 at the MIS 6/5.5 transition (Lambeck and Nakada, 1992; Potter and Lambeck, 2003). These models, however, require verification from field geology and a powerful argument against the glacio-hydro-isostatic model for T2 is the observation that MIS 5.5 marine deposits on apparently stable intermediate-field localities such as The Bahamas, Bermuda, California and Baja California are: "not significantly higher than those of MIS 5.5 age in far-field apparently stable localities such as Western Australia" (Muhs et al., 2002). It may indicate that glacio-hydro-isostatic recovery is rapid and that it is not yet possible to model the T2 event. Potter and Lambeck (2003) have also suggested that MIS 5.1 marine deposits above sea-level on the US Atlantic Coastal Plain (Wehmiller et al., 2008) result from glacio-hydro-isostasy. Yet Muhs et al. (2002) suggest that such a high sea-level should be expected, given the complete deglaciation of the Laurentide Ice Sheet at a time when Baffin Island was warmer than the Holocene (Miller et al., 1999; Wolfe et al., 2000). Summer temperatures, higher than present, in northern Fennoscandia during MIS 5.1 also suggest complete deglaciation of the Fennoscandian ice sheet (Valiranta et al., 2009). Thus, not only could the MIS 5.1 sea-level have been close to present, its effect on soft sediment coasts may have been significant and account for the MIS 5.1 sea-level at Gomez Pit, Virginia (Mirecki et al., 1995; Wehmiller et al., 2008). It is unlikely that the effects of glacio-hydro-isostasy on sea-level variability can be discovered for MIS 12/11(Termination V).

3 Location

3.1 Charleston, South Carolina, USA

The Atlantic Coastal Plain between the Fall Line and the edge of the Continental Shelf is the inner edge of a passive continental margin and its marine sediments range from Miocene to Holocene (Cronin, 1981). Their study has been characterised by two approaches; one geomorphological the other palaeontological. While the former recognised gently inclined marine terraces with shoreline features, it became evident that the terraces do not correspond to

Table 3. Estimates of the MIS 11 (406 ka) sea-level from assumptions of uplift rates using different ages and sea-levels for MIS 5.5 (see Method). Numbers in bold type are excluded because they lie at or are greater than two standard deviations. All numbers are rounded up.

116 ka 2 m	H	H^*	H^*-2	uplift m/ka	UC	S
Charleston	15	8	6	0.05	20	−5
Coorong CP	26	10	8	0.07	28	−2
Curacao	29	11	9	0.08	32	−3
Nome CP	23	12	10	0.09	37	**−14**
Rome CP	63	20	18	0.16	65	−2
Barbados	120	39	37	0.3	130	−2
Sumba I	190	60	58	0.5	203	−13
					MEAN	−3
					±	1

116 ka 4 m	H	H^*	H^*-4	uplift m/ka	UC	S
Charleston	15	8	4	0.03	12	3
Coorong CP	26	10	6	0.05	20	6
Curacao	29	11	7	0.06	24	5
Nome CP	23	12	8	0.07	28	−5
Rome CP	63	20	16	0.14	57	6
Barbados	120	39	35	0.3	122	−2
Sumba I	190	60	56	0.5	203	−13
					MEAN	0
					±	7

116 ka 6 m	H	H^*	H^*-6	uplift m/ka	UC	S
Charleston	15	8	2	0.02	8	7
Coorong CP	26	10	4	0.03	12	14
Curacao	29	11	5	0.04	16	13
Nome CP	23	12	6	0.05	20	3
Rome CP	63	20	14	0.12	49	**22**
Barbados	120	39	33	0.3	122	−2
Sumba I	190	60	54	0.47	191	−1
					MEAN	6
					±	7

124 ka 2 m	H	H^*	H^*-2	uplift m/ka	UC	S
Charleston	15	8	6	0.05	20	−5
Coorong CP	26	10	8	0.07	26	0
Curacao	29	11	9	0.07	26	3
Nome CP	23	12	10	0.08	33	**−9**
Rome CP	63	20	18	0.15	59	2
Barbados	120	39	37	0.3	122	−2
Sumba I	190	60	58	0.47	190	−1
					MEAN	0.5
					±	3

124 ka 4 m	H	H^*	H^*-4	uplift m/ka	UC	S
Charleston	15	8	4	0.03	12	3
Coorong CP	26	10	6	0.05	20	6
Curacao	29	11	7	0.06	24	5
Nome CP	23	12	8	0.06	24	−1
Rome CP	63	20	16	0.13	53	**10**
Barbados	120	39	35	0.3	122	−2
Sumba I	190	60	56	0.45	183	7
					MEAN	3
					±	4

Table 3. Continued.

124 ka 6 m	H	H^*	H^*-6	uplift m/ka	UC	S
Charleston	15	8	2	0.02	8	7
Coorong CP	26	10	4	0.03	12	14
Curacao	29	11	5	0.04	16	13
Nome CP	23	12	6	0.05	20	3
Rome CP	63	20	14	0.1	41	**22**
Barbados	120	39	33	0.3	122	−2
Sumba I	190	60	54	0.44	179	11
					MEAN	8
					±	6

132 ka 2 m	H	H^*	H^*-2	uplift m/ka	UC	S
Charleston	15	8	6	0.05	20	−5
Coorong CP	26	10	8	0.06	24	2
Curacao	29	11	9	0.07	28	1
Nome CP	23	12	10	0.08	32	−9
Rome CP	63	20	18	0.14	57	6
Barbados	120	39	37	0.28	114	6
Sumba I	190	60	58	0.44	179	11
					MEAN	2
					±	6

132 ka 4 m	H	H^*	H^*-4	uplift m/ka	UC	S
Charleston	15	8	4	0.03	12	3
Coorong CP	26	10	6	0.05	20	6
Curacao	29	11	7	0.05	20	9
Nome CP	23	12	8	0.06	24	−1
Rome CP	63	20	16	0.1	41	**22**
Barbados	120	39	35	0.27	110	10
Sumba I	190	60	56	0.5	203	−13
					MEAN	2
					±	8.5

132 ka 6 m	H	H^*	H^*-6	uplift m/ka	UC	S
Charleston	15	8	2	0.02	8	7
Coorong CP	26	10	4	0.03	12	14
Curacao	29	11	5	0.04	16	13
Nome CP	23	12	6	0.05	20	3
Rome CP	63	20	14	0.1	41	**22**
Barbados	120	39	33	0.25	101	**18**
Sumba I	190	60	54	0.4	162	**28**
					MEAN	9
					±	5

lithostratigraphical units although both were combined by Colquhoun (1965; Colquhoun et al., 1991). Six Quaternary marine lithostratigraphical units run north-east broadly in parallel with the modern shoreline (McCartan et al., 1984; McCartan, 1988). In each one, several lithofacies tend to grade into each other and consist of burrowed, fine to medium-grained sand with interbedded mud and shells, well-sorted fine to medium-grained sand and back-barrier muddy fine to medium-grained sand, mud and shells, as well as fluvial lithofacies. In comparison with modern and Holocene (Unit Q1) deposits, McCartan (1988) believed that "The highest back-barrier deposits mark approximately the highest

relative sea-level for each period of deposition". Back-barrier deposits up to 8 m occur in Unit Q2 (Wando Formation) and its late Pleistocene (MIS 5.5) age is based on U-series alpha ages on corals between 90 and 120 ka (McCartan et al., 1980; Szabo, 1985), amino acid ratios (McCartan et al., 1982), as well as relatively fresh minerals (McCartan et al., 1982). The Ladson Formation (Unit Q4) of Malde (1959) has back-barrier deposits up to 15 m. It is correlated with the Canepatch Formation at Myrtle Beach (SC) by a U-series alpha age of ∼450 ka and by mollusc and ostracode faunas (Cronin in McCartan, 1988). The occurrence of the coccolith *Gephyrocapsa* supports an age ascribed to MIS 11 (Cronin et al., 1984). Uplift rates calculated from event MIS 5.5 back-barrier deposits do not differ greatly from those of Cronin (1981) who used shoreline datums related to lithospheric flexure of the Coastal Plain-offshore Carolina platform and Carolina Trough. Tables 2 and 3 show estimates of the MIS 11 sea-level.

3.2 The Coorong Coastal Plain (SE South Australia)

A spectacular sequence of uplifted Plio-Pleistocene barrier dunes and back-barrier deposits runs inland across the Coorong Coastal Plain (Murray-Wallace, 2002). Back-barrier lagoon and estuarine deposits are preserved in interdune corridors and consists largely of unsorted litho-facies with gastropods and articulated bivalves. Along a transect from Robe to Naracoorte, the Woakwine deposits at 10 m have a TL age of 132±9 ka, and the East Avenue deposits at 26 m have a TL age of 414±29. Based on an uplift rate from an MIS 5.5 sea-level of 2 m the MIS 11 sea-level was calculated to be at −3 m at 420 ka (Murray Wallace, 2002). Tables 2 and 3 show estimates of the MIS 11 sea-level.

Some believe that the limit to TL dating is only about 100 kyrs. But much depends on the mineral used and the regional geology. In Australia, where dose rates are low, limits much greater than 100 kyrs may be expected (Berger, Huntley, Lancaster, personal communications, 2009), as in Spain, back to ∼1 Ma (Berger et al., 2008) and Alaska back to ∼800 ka (Berger et al., 1992). In the case of the Coorong Coastal Plain, there is a close correlation between TL and aminostratigraphical ages (Murray-Wallace, 2002). They are supplemented by some U-series and ESR ages on molluscs and corals (Murray-Wallace, 2002).

3.3 Curacao (Netherlands Antilles)

Curacao consists of off-lapping carbonate units forming marine terraces on a volcanic basement. Using TIMS ages Lundberg and McFarlane (2002) identified sea-levels of MIS 5.5 and MIS 11 events. The former has a well-preserved notch at 10.5 m with a TIMS age of 123.65±0.35 ka on coral. A TIMS age on coral of 412±14 ka dates "the base of the MIS 11 terrace" at 21 m, whereas the notch above it is at 37 m, so this may be older. The elevation used here is 29 m

as mid-point between 37 and 21 m. Tables 2 and 3 show estimates of the MIS 11 sea-level. If, however, the notch at 37 m is that of the MIS 11 sea-level, then six of the nine uplift correction calculations fail to meet the two standard deviations criterion. The remaining three give a sea-level estimate of 4±6, but all nine provide an estimate of 10±12.

3.4 The Nome Coastal Plain, Alaska

Six high stands of sea-level are found on the Nome Arctic Coastal Plain and consist of shorelines and superimposed shelf sequences with fossil evidence for climate that was as warm as, or warmer than, the present. Beaches, barrier islands and spits of the Pelukian marine transgression at 12 m (Brigham-Grette and Hopkins, 1995) are correlated with MIS 5.5 (Brigham-Grette, 1999). At 23 m a.s.l. lie shelf, beach and lagoonal sediments of the Karmuk Member of the Gubik Formation that is correlated with the Anvillian marine deposits of the Alaskan Coastal Plain (Kaufman, 1992; Kaufman and Brigham-Grette, 1993). They lie below glacial deposits of the Nome River Glaciation which is overlain by basaltic lava with ^{40}Ar/^{39}Ar age estimates of 470±190 ka (Muhs et al., 2004). The Anvillian marine deposits are dated with AAR age estimates of about 475 ka. They have been correlated with the middle of the *Rhizosolenia barboi* diatom zone between 430 and 360 ka (Pushgar et al., 1999). Tables 2 and 3 show estimates of the MIS 11 sea-level.

3.5 San Paulo Formation, Lazio, Italy

Downstream from Rome, fluviodeltaic sediments include the San Paulo Formation, silty sand with ostracodes, foraminifera as well as *Cerastoderma* and *Tellina* that indicate a brackish water environment (Karner and Marra, 1998). Its upper surface lies at 63 m (Karner and Marra, 1998; Karner and Renne, 1998; Karner and Marra, 2003). The formation includes tephra with ^{40}Ar/^{39}Ar ages of 416±11 and 407±11 (Karner and Marra, 2003). Downstream a marine terrace with a shoreline angle at 20 m is correlated with other sites in Lazio, notably Casale di Statua, that have definitive MIS 5.5 palaeontological and aminostratigraphical ages (Giordano et al., 2003; Ferranti et al., 2006). Tables 2 and 3 show estimates of the MIS 11 sea-level.

3.6 Barbados

Barbados has long been the testing ground for U-series ages on coral terraces (alpha and then TIMS ages from ^{230}Th and ^{231}Pa/^{235}Th) (Bender et al., 1979; Broecker et al., 1968; Mesolella et al., 1969; Edwards et al., 1997; Gallup et al., 2002). ESR ages on coral samples from sites determined by detailed geomorphological field mapping of former sea cliffs, erosional notches, reef crests, and wave cut terraces, at elevations surveyed to an accuracy of 1 m, demonstrated

18 separate stands of sea-level compared with only 11 previously recognised (Schellmann and Radtke, 2004a, b). The highest MIS 5.5 elevation (Terrace T-5b) is at 39 m, with an ESR age of 132 ka. That of MIS 11 (Terrace T-13) is at 120 m with an ESR age of 410 ka (Schellmann and Radtke, 2004a, b). Tables 2 and 3 show estimates of the MIS 11 sea-level.

3.7 Sumba Island, Indonesia

A flight of marine terraces at Cape Laundi on the northern side of Sumba Island Indonesia was mapped by Jouannic et al. (1988) (map in Bard et al., 1996), the oldest of which was correlated with MIS 27 (Pirazzoli et al., 1993). ESR ages on corals correlated with MIS 15 and MIS 9 showed an "uplift trend" of 0.49 m/ka (Pirazzoli et al., 1993). Bard et al. (1996) used TIMS ages that identified the 5.1, 5.3, 5.5 (between 119 and 132 ka) and MIS 9 (∼305 ka), and suggested that the average uplift rate lies between 0.2 to 0.5 m/ka. The MIS 5.5 sea-level (reef complex II) lies at 60 m with TIMS ages close to 130 ka (Bard et al., 1996). Reef terrace III2 at 190 m has ESR ages of 322 ± 48, 327 ± 49 and 397 ± 59 ka, and a ^{230}Th age of >300 ka. It lies below terrace IV1 that has ESR ages of 584 ± 88 and 609 ± 90 (Pirazzoli et al., 1993). Thus, terrace III2 is likely to mark the MIS 11 sea-level. Tables 2 and 3 show estimates of the MIS 11 sea-level.

4 Discussion

4.1 MIS 11 sea-level at 1.5 m ± 3

A range of possible sea-levels for MIS 11.3 from uplift correction calculations based on different assumptions for the MIS 5.5 sea-level and its age is presented in Fig. 1, Tables 2 and 3. The mean sea-level calculation for MIS 11.3 is 3 ± 4 m (n=9), but if outliers at two standard deviations or greater are removed the mean value is reduced to 1.5 m±3 (n=7). This is the same as the preferred calculation of Schellmann and Radtke (2004a, b) for the MIS 11 sea-level of 1.5 m (average of 5 m for Terrace T13 at 410 ka and −2 m sea-level for Terrace T12 at 398 ka) based on uplift correction using a 132 ka MIS 5.5 aged sea-level at 2 m. The Coorong Coastal Plain calculation of −3 m sea-level at 420 ka is also based on a 2 m sea-level for MIS 5.5 (Murray-Wallace, 2002). Because of their detailed geomorphology and geochronological age estimates Barbados and the Coorong Coastal Plain are arguably the most important locations under consideration. Both lie within the 1.5 m ±3 band. Schellmann and Radtke (2004a, b) found that their Barbados estimates best fitted with the MIS 5.5 sea-level of 2 m from the Gawler Craton of Murray-Wallace and Belperio (1991), and not with estimates based on an MIS 5.5 sea-level of 6 m. Estimates of MIS 11 sea-levels based on uplift correction from an MIS 5.5 sea-level at 6 m tend to lie on the higher side although none exceed ∼9 m.

4.2 High MIS sea-levels in Bermuda, Bahamas, Hawaii and Sussex (UK)

Higher MIS 11 sea-levels (∼20 m) have been proposed in Bermuda (Hearty, 1998a, 2002; Hearty et al., 1999; Olson and Hearty, 2009), and have been widely adopted (e.g. Howard, 1997; Rohling et al., 1998; Droxler and Farrell, 2000). Similar high sea-levels have also been proposed in The Bahamas (Kindler and Hearty, 2000) and Oahu, Hawaii (Hearty, 2002).

In Bermuda, MIS 11 marine deposits have been described in karstic caves at Government Quarry. They occur at 18 m at Dead End Cave (Hearty et al., 1999) and 21 m at Calonectris Cave (Olson and Hearty, 2009; van Hengstum et al., 2009). At Government Quarry a wide range of TIMS ages (127–680 ka) on "flowstone" in the succession of deposits are: 127 ± 1.6 ka, 420 ± 30 ka, 525 ± 50 ka and 680 ± 130 ka at the Dead End Cave (Hearty et al., 1999); 442 ± 123 ka, 503 ± 110 ka at Wilkinson Quarry (Olson and Hearty, 2009); and 125 ± 4 ka, 312 ± 30 ka, 360 ± 40 ka and 480 ± 50 ka at caves UGQ4 and UGQ5 (McMurty et al., 2007).

The Calonectris Cave deposits have, however, been attributed to a mega tsunami (McMurty et al., 2007) and other possibilities include tectonic uplift. Thus, if the highest MIS 5.5 marine deposits in Bermuda at 6 m (Harmon et al., 1983), with six TIMS ages between 125 and 113 ka for the Rocky Bay Formation (MIS 5.5) (Muhs et al., 2002) are subject to uplift correction, the mean sea-level for any MIS 11 sea-levels is 5 ± 2 m. Because the Fort St Catherine Formation (TIMS ∼80 ka – Muhs et al., 2002) also lies above present sea-level, it may lend support to an uplift hypothesis (but see also Sect. 2 Method). Furthermore, at Rocky Bay (Land et al., 1967), the Belmont beach facies of MIS 7 is overlain unconformably by the Devonshire marine unit of the Rocky Bay Formation of MIS 5.5 age, which also points to uplift of the MIS 7 unit fashioned when sea-level was below present (Bard et al., 2002; Dutton et al., 2009). What, then, is so sacrosanct about the tectonic stability of Bermuda?

A further possibility is that of vertical transportation of fauna and sediments by hurricane winds. Subsequent entrainment and transport by fluvial means may have been followed by emplacement in phreatic cave systems, which were subsequently intersected by marine cliff retreat. The present position of the karstic caves at Government Quarry, up to 100 m from the Holocene shoreline because of quarrying, lends plausibility to this hypothesis. Hurricanes are well-known for their wave generated effects and, for example, in 2004 Hurricane Ivan produced severe wave effects up to 27 m (Stone et al., 2005). During MIS 5.5 large boulders were emplaced some 20 m a.s.l. on Eleuthera in the Bahamas (Hearty, 1998b).

Undated marine sediments at 18 m on Eleuthera have been correlated with MIS 11 (Hearty, 1998a; Hearty et al., 1999). But they are interpreted as Holocene deposits emplaced during storm events by Mylroie (2008), who pointed out that

the highest marine deposits on the island with TIMS ages of 131 to 119 ka (Chen et al., 1991) lie no higher than 6 m.

The Kaena marine deposits on Oahu, Hawaii, occur at ∼30 m (Stearns, 1966, 1978) and have been ascribed to MIS 11 (Hearty, 2002). This, however, is in conflict with TIMS ages of 532 +130/−70 ka and 529 +47/−35 ka that suggest the age of the Kaena sea-level event is 500–600 ka (Muhs et al., 2004).

The estimated MS 11 sea-level proposed in Sussex, England (Bowen, 1999) and cited by Olson and Hearty (2009) was withdrawn when it became clear that the stratigraphical geometry of complex sediments on the coastal plain, which included bivalves and gastropods with amino acid ratios correlated with MIS, 5.5, 7 and 9, did not provide a definitive elevation for the MIS 5.5 sea-level (Bowen, 2003a). But the aminostratigraphical correlation of the marine sands at Boxgrove with the MIS 11 marine clays (Hoxnian) in the Nar Valley, Cambridgeshire (Lewis, 1999) remains unchanged (Bowen, 2003b).

4.3 Ice volume and sea-level

Shackleton (1987) estimated that the MIS 12 sea-level was some 15% lower than that of the Last Glacial Maximum. Given an LGM sea-level of −130 m (Clark and Mix, 2002) then on Shackleton's estimate the MIS 12 sea-level would have been ∼−140 m. This is supported by an estimate of −140 m from a hydraulic model of water flow though the Strait of Bab-el-Mandab in the Red Sea (Rohling et al., 1998), notwithstanding a subsequent estimate based on inferences drawn from δ^{18}O measurements (Rohling et al., 2009).

With an MIS 11 sea-level at ∼20 m then, the MIS 12/11 sea-level rise would have been ∼160 m. This compares with only 130 m of sea-level rise at the MIS 2/1 transition. Where did the extra 30 m of sea-level come from? What melted? Could it happen again (Chappell, 1998)? Hearty et al. (1999) suggested that the melting of Antarctic ice caused the MIS 11 high sea-level. Others (Rohling et al., 2009), however, estimated that a 20 m rise in sea-level would involve the melting of both West Antarctic and Greenland ice-sheets. Note, the Greenland ice sheet did not melt entirely during MIS 7 (Suwa et al., 2006) when sea-level was below present (Bard et al., 2002; Dutton et al., 2009), and the potential to raise present sea-levels with contributions of meltwater from the Greenland or Antarctic ice sheets is dominated by uncertainties (Alley et al., 2005).

An MIS 11 sea-level at or close to present does not require melting of the West Antarctic and Greenland ice sheets because only 140 m of sea-level rise is required. This is only 10 m more than the MIS 2/1 rise in sea-level, a volume readily accounted for by the melting of mid-latitude Northern Hemisphere ice sheets that were at their greatest extent of the last 0.5 Ma in MIS 12 (Sibrava et al., 1986; McManus et al., 1999).

5 Conclusions

Uplift correction, based on the assumptions stated at the outset, shows that the sea-level of MIS 11 at 406 ka was closer to present than previously suggested.

An MIS 11 sea-level close to present is consistent with inferences drawn from benthic oxygen isotope stratigraphy (McManus et al., 2003) and lies within the band of sea-levels similarly estimated by Waelbroeck (2002).

Data from uplifted shorelines and inferences from benthic oxygen isotope stratigraphy suggest that both sea-level and global ice volume, though not necessarily its regional location, may have been broadly similar to those of the present during MIS 11.

This study of geological and geomorphological actualities in the field on the global shore at selected locations with age estimates for the MIS 11 shoreline, does not support an MIS 11 sea-level at ∼20 m.

There is no need to invoke additional melting of the West Antarctic and Greenland ice sheets for the rise in sea-level from an MIS 12 low stand at ∼−140 m. The melting of Northern Hemisphere mid-latitude ice-sheets at their greatest extent during MIS 12 (Sibrava et al., 1986; McManus et al., 1999) yielded the greatest transfer of continental ice volume to the oceans of the last 0.5 Ma.

Orbital similarities between the MIS 11 and the present interglacial are the result of the 413 kyrs Milankovitch pacing (Berger and Loutre, 2002). Compared with the duration of the present interglacial of 11.6 kyrs, MIS 11 lasted over 60 kyrs and was the longest interglacial of the last 0.5 Ma (Loutre and Berger, 2003). Given similar natural variability and configurations of continents, mountain ranges, seaways and orbitally controlled solar radiation, it is not unreasonable to suppose that in the "exceptionally long interglacial ahead" (Berger and Loutre, 2002) continental ice-volume and sea-level will also be similar to MIS 11: that is, subject to millennial and sub-millennial forcing.

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