Coral Reefs (2003) 22: 257–270
DOI 10.1007/s00338-003-0315-4

REPORT

M. A. Toscano · I. G. Macintyre

Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmata* framework and intertidal mangrove peat

Received: 8 November 2001 / Accepted: 10 September 2002 / Published online: 3 September 2003

Abstract A corrected western Atlantic Holocene sea-level curve was constructed from 145 calibrated ^{14}C and TIMS U-Th dates from shallow *Acropora palmata* framework and intertidal *Rhizopora mangle* peat from the Florida Keys, Belize, and the wider Caribbean. Data include both previously published and newly reported coral and peat dates. With the elevations of corals restricted to positions below sea level and those of peats to intertidal and higher levels, a curve bracketed by corals below and peat above effectively delineates the positions of a rising Holocene sea. From 3–11 ka, the corrected curve shifts progressively to older calibrated ages, reaching an ~1-kyr increase at −21 m MSL (mean sea level). Elevations and calibrated ages of samples from each locality in the wider Caribbean region constitute an important database for future refinement with glacio-hydro-isostatic elevation corrections from 3-D Earth models. In future studies of the history of western Atlantic coral reefs, scientists will be able to relate calibrated radiocarbon dates to this sea-level curve to determine paleo water depths and rates of sea-level rise.

Keywords Sea-level rise · *Acropora palmata* · Mangrove peat · Radiocarbon calibration · Paleo water depths · Corrected Holocene sea-level curve · Glacio-hydro-isostacy

Introduction

Sea-level rise (SLR) has effected widespread physical and ecological coastal shifts during the past 20 ka of deglaciation and subsequent local relative sea-level changes during the Holocene and historic times (Fairbanks 1989; Intergovernmental Panel on Climate Change 1996). Reconstructed past climate changes and rapid SLR effects on shallow coral reef and coastal mangrove environments have been used to predict the current and future effects of anthropogenic climate forcing and accelerated rates of SLR (e.g. Ellison and Stoddart 1991; Ellison 1993; Guilderson et al. 1994; Parkinson et al. 1994; Field 1995; Graus and Macintyre 1998). Sea-level reconstructions are essential in order to understand the relationship of past rates of SLR with the patterns of other climate proxy records, with the timing of orbital forcing (Berger and Loutre 1991), and with the response of the affected ecosystems. However, the dating of sea-level indicators, particularly from marine sources, must be accurately expressed in terms of calendar years, and be correlative to the same precise time scales calculated for orbital variations, from dendro-chronologic and sclero-chronologic records and from well-dated terrestrial data.

The presumed tectonically stable areas of the Caribbean (Fig. 1) contain a suite of ^{14}C-dated Holocene coastal and nearshore marine data with well-defined relationships with sea level, tide range, and/or water depth. A great deal of previously published sea-level-related data exist as raw ^{14}C dates on the reef-crest (sea-level tracking) coral *Acropora palmata*, and on peat deposits presumed to consist predominantly of remains of the intertidal red mangrove *Rhizopora mangle*. These raw ^{14}C dates were determined using the Libby ^{14}C half-life of 5,568 years rather than the true ^{14}C half-life of 5,730 years. They are non-conventional (neither analyzed nor corrected for $\delta^{13}C$) and (if from coral) do not account for the oceanic reservoir effect on the western tropical Atlantic and Caribbean region (approximately +400 years). As such, they are not valid calendar ages and lack potential for correlation with each other (marine vs. terrestrial data), with other paleoclimate records, or with the timing of orbital variations affecting global climate. They also cannot provide an accurate temporal framework for rapid sea-level changes or for the timing of reef responses to related climatic

M. A. Toscano (✉) · I. G. Macintyre
Department of Paleobiology, Smithsonian Institution,
National Museum of Natural History, MRC 125,
Washington, District of Columbia 20560, USA
E-mail: mtoscano@sprintmail.com

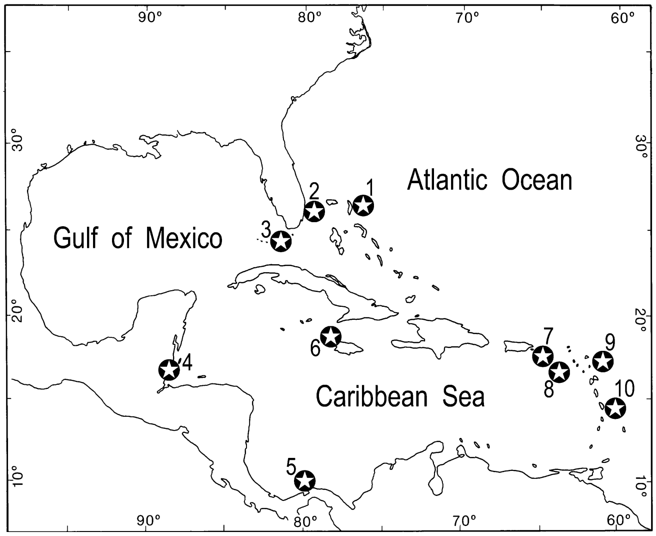

Fig. 1 Location map of sample sites: *1* Abaco, Bahamas (*A. palmata*); *2* East Coast, Florida (*A. palmata*); *3* Florida Keys (*A. palmata*; mangrove peat); *4* Belize (mangrove peat); *5* Galeta Point, Panama (*A. palmata*); *6* Jamaica (mangrove peat); *7* Vieques, Puerto Rico (*A. palmata*); *8* St. Croix, US Virgin Islands (*A. palmata*); *9* Antigua (*A. palmata*); and *10* Martinique (*A. palmata*). See Tables 1, 2 and 3 for original references, sample information, and age data. Glacial-hydro-isostatic elevation offsets contributing to differences in relative sea-level histories among these sites have been suggested by models (Lambeck et al. 2002) but have not been specified for use in calibrating the elevations in this paper. The largest modeled elevation offsets (up to 3 m) would occur in the Florida data set, with progressively smaller offsets southward towards the island of Barbados [southeast of Martinique (no. 10)]

perturbations. Bard (1998) presents an excellent summary of the implications.

Calibration data are now widely used to further refine the true ages of radiocarbon-dated samples (Stuiver et al. 1998a, 1998b). Calibration increases age accuracy by accounting for temporal variations in atmospheric $^{14}C/^{12}C$, and allows the calibrated dates to be referenced to calendar years and to be used in combination with high-precision thermal ionization mass spectrometric (TIMS) U-Th dates, or "true" ages (Bard et al. 1998; Toscano and Lundberg 1998). The combination of $\delta^{13}C$ and marine reservoir correction with marine (for coral) and atmospheric (for peat) calibration shifts the original ^{14}C data to older values; the offset increases with increasing sample age (Bard et al. 1990). If the entire ^{14}C sea-level database is calibrated, progressively older portions of the sea-level record will shift back in time to a significant degree, re-establishing the timing of rate changes and enabling the ^{14}C-derived record to be more accurately correlated to other precisely dated records.

We present a record of the Holocene transgression for the western Atlantic, incorporating all available (previously published and new) sea-level indicator data. We have calibrated all previously published and new data from raw ^{14}C dates to calendar ages in order to improve the temporal framework of the record. We then combined the calibrated *A. palmata* framework and intertidal mangrove (predominantly *R. mangle*) peat dates with published TIMS U-Th-dated corals from the stable Florida and Bahamian margins, and additional published peat data (calibrated herein) from Belize and Jamaica to cover the wider Caribbean. The juxtaposition of the intertidal peat record stratigraphically above the record of concurrent reef crest corals ensures better-constrained estimates of sea-level elevation, as well as of the water depths in which the *A. palmata* framework grew. We also assess rates of SLR for the wider Caribbean from the combined curve, and compare the sea-level elevations with those of the Barbados record for the period over which they overlap. The resulting regional sea-level record does not yet incorporate recent glacio-hydro-isostatic elevation model simulations, which suggest differences in relative sea-level histories for some of the contributing localities (Lambeck et al. 2002). This new curve can reasonably be utilized with newer calibrated ^{14}C data throughout the tectonically stable areas of the Caribbean from 11 ka to the present until such model corrections become available for all the sampled localities and can be applied to refine the sample elevations.

Previous work

The first detailed accounting of SLR during the last deglaciation in the Caribbean (Fairbanks 1989) revealed two distinct intervals of rapid SLR. These intervals were related to meltwater pulses [MWP 1A, 14,200 calendar years b.p. (cal BP); and MWP 1B, 11,400 cal BP) that caused sea level to rise 24–28 m 1,000 yrs^{-1}, which in turn resulted in hiatuses in the shallow-water *A. palmata* accumulations on the insular slope of Barbados. The most recent portion of Fairbanks' (1989) curve, from 7,800 years B.P. to the present, was based on data from Lighty et al. (1982), consisting of dates from *A. palmata* framework from relict shelf-edge reefs and younger reefs.

Lighty et al.'s (1982) database constituted the first coral-based, relatively complete (10 ka) Holocene *minimum* sea-level curve for the tropical western Atlantic. The minimum sea-level curve was developed using Caribbean-wide *A. palmata* sampled from well-documented shallow reef-crest framework [e.g. Lighty et al. (1978), east Florida] or cored from reef crest features in other localities [referenced in Lighty et al. (1982)]. *A. palmata* exhibits growth rates of as much as 14 mm $year^{-1}$, and may be a continuous tracer of SLR, provided that the rate of rise does not exceed this maximum growth rate.

Lighty et al.'s (1982) use of *A. palmata* framework for sea-level reconstructions required that specimens were sampled specifically from reef-crest facies exhibiting interlocking framework growth, thus allowing the assumption that the samples had grown within the restricted depth range (< 1 to 5 m) typical for this facies. Other cited advantages of *A. palmata* framework include the likelihood of minimal compaction of thick branches.

Neither the stated sample elevation errors (± 15 cm) nor the ^{14}C date ranges significantly affected the positioning of the curve, which was set "a short distance above" the shallowest-occurring corals on the time-depth plot. Lighty et al.'s (1982) curve was defined as a minimum curve (keeping all coral submerged), yet the sea-level elevations it predicted exceeded those of pre-existing curves, which were based on various marine and marginal marine data [Curray (1961, 1965): combination of mollusk shells, wood, and peat; Redfield (1967): peat; Neumann (1971): peat; Milliman and Emery (1968): shells]. It provided a framework for future curves or curve segments which might indicate higher sea levels, provided any additional submersion did not exceed more than 5 m (i.e. deeper than the maximum reef crest framework depth range of *A. palmata*).

Blanchon and Shaw (1995) essentially reproduced the record of Fairbanks (1989) and Lighty et al. (1982). They reclassified the meltwater pulses of Fairbanks (1989) as "catastrophic rise events" (CREs) to indicate the inability of *A. palmata* framework to keep pace during those episodes. Blanchon and Shaw (1995) noted a gap in more recent radiocarbon dates and suggested a third CRE hiatus at approximately 7.6 ka, during which an *A. palmata* reef-crest facies was unable to keep up with a SLR rate estimated at > 45 mm year^{-1}. Bard et al. (1996) reported no detectable meltwater pulse at 7.6 ka in the continuous Tahiti coral record [see also Montaggioni et al. (1997); Blanchon (1998); Montaggioni and Bard (1998)]. Toscano and Lundberg (1998) introduced new age data from a previously unsampled portion of the Holocene record in Florida, consisting of several TIMS U-Th-dated *A. palmata* samples which partially filled this gap. Toscano and Lundberg (1998), who made a first attempt to calibrate the previous ^{14}C-dated sea-level data for Florida, also pointed out that, even without the addition of new data into the gap's time-depth space, the rate of SLR for that interval was too low to preclude *A. palmata* framework accretion, and the gap was likely an artifact of incomplete sampling of the full record of Holocene reefs. Precht et al. (unpublished data) produced new ^{14}C dates from another previously unsampled portion of the Florida Holocene, which further fill the data gap and verify that *A. palmata* framework was able to accrete at non-maximal rates of SLR during that period. The portions of the Holocene record sampled by Toscano and Lundberg (1998) and Precht et al. (unpublished data) consist of off-shelf relict reef ridges which form multiple tracts in some areas (Enos 1977; Lighty et al. 1978). The physical separation of the ridges (whether gradational or distinct) has been attributed to reef termination and backstepping, possibly due to periods of rapid SLR (e.g. Blanchon and Shaw 1995) or to shelf flooding and introduction of turbidity into the reef, which is inimical to coral survival (Lighty et al. 1978). The increasing availability of dates from most of these reefs indicates overlapping age ranges and at least some contemporaneous reef growth between adjacent tracts. Clearly, neither SLR nor any of a number of possible inimical conditions should be invoked as "drowning" or "backstepping" mechanisms to account for their physical separation, if they coexisted over similar time frames.

In addition to corals, intertidal mangal (mangrove-based) communities consisting predominantly of the red mangrove (*Rhizopora mangle*) produce peat deposits which provide ^{14}C-datable material deposited in a well-defined relationship to tidal range and hence to sea level (e.g. Scholl et al. 1969; Robbin 1984; Digerfeldt and Hendry 1987; Boardman et al. 1988; Ellison and Farnsworth 2001). As such, *R. mangle* and associated intertidal peats can provide essential upper-limit information for the actual position of sea level, above the elevation of contemporaneous coral reef crest growth. Sea-level curves spanning the past 5 ka were developed from *R. mangle* peat data on the southwest Florida shelf [Gulf of Mexico: Scholl (1964a, 1964b); Bloom (1967); Scholl and Stuiver (1967); Scholl et al.(1969)]. Scholl (1964a, 1964b) used only fibrous basal peats (overlying bedrock or freshwater sediment, and therefore least likely to have been affected by compaction) to mark the base of the transgressive sequence and to reconstruct SLR on the West Florida Shelf. The maximum depth from the water surface to Pleistocene bedrock along the west coast of Florida is only 3.5 m (Enos 1977); thus the sea-level data from those studies do not cover the depth range or time frame of the southeast (Atlantic) Florida reef tract.

Reef-tract mangrove-peat data and laminated $CaCO_3$ (caliche or soilstone) crusts (now submerged) from the southeast Florida shelf (Florida Keys) and reef tract were ^{14}C dated and used to reconstruct sea-level change for the past 8 kyrs in that region (Robbin 1981, 1984). These earliest peats (described generically as "mangrove peats") are preserved below Holocene reef deposits along the Florida Keys shelf edge. While the caliche dates were indicative of the period of subaerial exposure of the shelf edge, the mangrove peats dated the initial transgression of the sea over the shelf edge and subsequent flooding of the platform. Although Florida peat data should be able to constrain the position of sea level to within ± 0.6 m (the local tidal range in the Florida Keys), Robbin's (1984) curve is positioned to submerge many of the samples at depths exceeding 0.6 m. A peat-based sea-level curve for Tobacco Range, a group of islands presently covered by mangroves in the central Belize Lagoon [23 samples; Macintyre et al. (1995)] records the mid–late Holocene SLR from 7 ka to the present against the Lighty et al. (1982) coral-based sea-level curve. In this case all but two problematic peats plotted on or above the coral-based curve (Macintyre et al. 1995). Macintyre et al. (2003) obtained ^{14}C dates on 24 peats (and three wood samples) cored from Twin Cays, Belize, spanning an age range of 380–7,700 years B.P. Other peat data from Belize include several dates from a transect leeward of Carrie Bow Cay (Shinn et al. 1982), which extend the record back to 11 ka, and the deepest peat date from Boo Bee Patch

Reef (Halley et al. 1977) at –18 m MSL. In Jamaica, Digerfeldt and Hendry (1987) constructed two submergence curves from a variety of local peat types, by placing the sea-level elevation curve above the elevation range of all peat data (including sedge peats). By submerging all peat data, including fresh-water types, Digerfeldt and Hendry's (1987) curve exceeded the minimum coral-based curve of Lighty et al. (1982) by approximately 2.5 m. Digerfeldt and Hendry (1987) cited the difference as a precaution to investigators against using the minimum levels and strongly suggested that individual localities develop site-specific sea-level curves. None of the records discussed above has incorporated differential glacio-hydro-isostatic effects on sample elevations from the range of Caribbean sites involved in this sea-level reconstruction, since the region has been assumed to be tectonically stable over at least the time frame of the Holocene. Lambeck et al. (2002) recently modeled glacio-hydro-isostatic offsets for the Caribbean and Barbados, and cautioned that the differential isostatic effects between the Caribbean sites used herein can be substantial, and a source of observed elevation scatter in both data sets. This topic is reviewed in full by Peltier (2002). Specific corrections/equations for the range of localities in this paper were not provided by Lambeck et al. (2002). We will nevertheless show how the age-calibrated version of the regional sea-level curve constructed from coral and peat time-depth data compares with the uncalibrated version, and offer the calibrated data set as a basis for future refinements to the sea-level curve based on 3-D Earth geophysical model elevation corrections.

Methods

Samples

Peat data from the Florida Keys (Robbin 1984), Belize [Tobacco Range: Macintyre et al. (1995); Twin Cays: Macintyre et al. (2003); the transect leeward of Carrie Bow Cay: Shinn et al. (1982); Boo Bee Patch Reef: Halley et al. (1977)], and Jamaica (Digerfeldt and Hendry 1987) comprised the intertidal portions of the sea-level database (Table 1) and provide maximum sea-level constraints when combined with contemporaneous reef crest *A. palmata* data (Tables 2 and 3). The peats have *not* all been demonstrably identified as the species *R. mangle*, specifically occurring within a fringing, tidal facies. Tobacco Range and Twin Cays samples were taken from long (up to 10-m thick) sections of continuous peat deposits cored in transects across these mangrove ranges, crossing several mangrove subenvironments and adjacent shallow marine areas. According to Woodroffe (1995), surveys across mangrove ranges in Belize, located 15–20 km offshore and leeward of the barrier reef, indicated a 15-cm elevation range over which several mangrove subenvironments occur, with *Avicennia* (black mangrove) occurring more often at the top of this range, flooded mainly by high spring tides. Portions of the long sections from both Tobacco Range (Macintyre et al. 1995) and Twin Cays (Macintyre et al. 2003) consist of fine-fibered (decayed) peat with no identifiable macroscopic remains. Because these long sections consist almost exclusively of mangrove peat (with no terrestrial sediment input or vegetative contamination), which in these areas exists over a very small, tidally influenced elevation range [total relief <0.25 m; Macintyre et al. (1995)], we can test whether the incremental portions of these deposits track sea level up the section. The Jamaica database (Digerfeldt and Hendry 1987) consists of a mixture of salt- and fresh-water types; only those identified as *R. mangle* are used in this reconstruction. All ^{14}C age data from peat samples required calibration. We refer to the paleoenvironmental assessments of the original authors when assessing the relationships of peat data to sea level, and note exceptions and outliers in the Results section.

The minimum sea-level constraint in our reconstruction comes from reef crest *A. palmata* age data from the Florida Reef tract [Lighty et al. (1982); Toscano and Lundberg (1998); Precht et al., unpublished data; Tables 2 and 3], and other localities spanning the wider Caribbean [Lighty et al. (1982); Macintyre et al. (1985); Tables 2 and 3)]. Coral samples were obtained from sub-sea excavations (Lighty et al. 1982) and reef crest cores (Macintyre et al. 1985; Toscano and Lundberg 1998) and largely represent intact framework spanning a predictable depth range for *A. palmata* growing in clear Caribbean waters.

Rationale and techniques for calibrating radiocarbon dates

The radiocarbon dates obtained from the original studies cited herein had not been corrected in any way, and hence were published as basic ^{14}C "dates" based on the Libby half-life (5,568 years). No $\delta^{13}C_{PDB}$ measurements were made on any of these samples (specifically stated in the publications), and all predate the time when many laboratories routinely began to normalize all samples using the standardized $\delta^{13}C_{PDB}$ value of $-25‰$ to arrive at "conventional" ^{14}C ages. None had been calibrated and none of the mixed layer marine samples (corals) incorporates an oceanic reservoir correction. In order for ^{14}C age data from mixed-layer marine samples (corals) to be comparable with terrestrial ^{14}C chronologies and absolute chronologies from TIMS U-Th data, all ^{14}C ages from shallow marine corals must be corrected for the $^{14}C/^{12}C$ difference between atmospheric CO_2 and the ΣCO_2 of the mixed layer or surface ocean, which is not in isotopic equilibrium with (i.e. is older than) the atmosphere (Bard 1988). The apparent, or reservoir, age of the mixed layer is $\sim+400$ years at 30°N latitude based on recent planktonic foraminiferal studies covering the last 40 kyr (Bard 1988). The lack of correction for fractionation and reservoir effect was deliberate by the respective investigators, in part because the subtracted 400-year reservoir correction is effectively cancelled by the standardization of $\delta^{13}C$ values of marine samples to $-25‰$ (standard for wood), which adds 400+ years to uncorrected marine ^{14}C dates. These researchers also have traditionally wished to keep their dates consistent with all previously published dates for comparison purposes, particularly with respect to existing uncorrected sea-level curves.

Coral ^{14}C dates were calibrated using the CALIB 4.3 program (Stuiver and Reimer 1993) with the option to input an estimated $\delta^{13}C_{PDB}$ value of 0.0‰. The marine calibration data set C (Stuiver et al.1998a, 1998b) was used, but the CALIB program automatically incorporated a time-dependent global ocean reservoir correction [$\approx$400 years; CALIB Manual version 4.1, Stuiver and Reimer (1993)]. The difference in age between the local ocean reservoir and modeled values (ΔR) was set at -5 ± 20 [Darden Hood, Beta Analytic, personal communication; Stuiver and Braziunas (1993)]. In addition to the CALIB-based calibrations made, all of the coral data were calibrated separately by Beta Analytic, with matching results.

Mangrove peats may be grouped with C3 plants whose $\delta^{13}C_{PDB}$ values are approximately $-27\pm7‰$ (Smith and Epstein 1971). None of the mangrove samples were analyzed for ^{13}C fractionation (specifically stated in the published sources) and were calibrated as non-conventional radiocarbon ages using a $\delta^{13}C_{PDB}$ value of $-27\pm0.2‰$ and the atmospheric calibration data set A [CALIB Manual version 4.1; Stuiver and Reimer (1993); Stuiver et al. (1998a, 1998b)]. As with coral data, calibrations made with the CALIB program were checked with calibrations made by Beta Analytic and found to agree.

Table 1 Peat age and elevation data [sources indicated by references *1–5*: *1* Macintyre et al. (1995); *2* Shinn et al. (1982); *3* Macintyre et al. (2003); *4* Robbin (1984); *5* Digerfeldt and Hendry (1987)]. Peats were not routinely identified and likely represent mixed species. All peat data were calibrated to calendar (*Cal BP*) years as described in the text. *(BP)* denotes an interpreted basal peat. Entries marked with an *asterisk* indicate problematic data as described in the text. Sampling method: *VC* vertical core; *HC* horizontal push core into subsea outcrop/vertical wall of peat; *E* subsea excavation. Jamaica (ref. 5) samples were taken via hand-auger, hammer-driven split-spoon sampler, or vibracoring (not specified per sample). *MSL* Mean sea level

Core/sample/ ID (ref.)	Locality	Sampling method	Sample elevation (m MSL)	Tide range (m)	^{14}C date (years B.P.)	Range (years)	^{14}C age		Cal BP (calendar years)
							Conventional (years)	Range (years)	
Belize									
TR1 (1)	Tobacco Range	VC	−0.97	0.21	2,090	70	2,060	70	2,000
*TR1 (1)	Tobacco Range	VC	−3.30	0.21	2,670	90	2,640	90	2,760
TR1 (1)	Tobacco Range (BP)	VC	−7.91	0.21	6,920	80	6,890	80	7,700
TR2 (1)	Tobacco Range	VC	−1.16	0.21	1,710	60	1,680	60	1,560
TR2 (1)	Tobacco Range	VC	−3.01	0.21	3,550	90	3,520	90	3,830
TR2 (1)	Tobacco Range	VC	−3.84	0.21	5,450	75	5,420	80	6,240
TR2 (1)	Tobacco Range (BP)	VC	−8.34	0.21	6,550	95	6,520	100	7,430
TR3 (1)	Tobacco Range	VC	−0.62	0.21	2,380	90	2,350	90	2,350
TR3 (1)	Tobacco Range	VC	−3.51	0.21	4,790	80	4,760	80	5,530
TR3 (1)	Tobacco Range (BP)	VC	−5.82	0.21	6,040	100	6,010	100	6,840
TR4 (1)	Tobacco Range	VC	−6.33	0.21	5,510	110	5,480	110	6,290
TR4 (1)	Tobacco Range	VC	−6.75	0.21	6,010	80	5,980	80	6,780
TR4 (1)	Tobacco Range (BP)	VC	−7.53	0.21	6,290	90	6,260	90	7,220
TR5 (1)	Tobacco Range	VC	−4.81	0.21	5,470	100	5,440	100	6,280
TR5 (1)	Tobacco Range	VC	−7.34	0.21	6,310	90	6,280	90	7,240
TR5 (1)	Tobacco Range (BP)	VC	−9.93	0.21	6,920	100	6,890	100	7,700
TR6 (1)	Tobacco Range	VC	−6.97	0.21	5,790	110	5,760	110	6,540
TR6 (1)	Tobacco Range	VC	−8.25	0.21	6,570	90	6,540	90	7,440
TR6 (1)	Tobacco Range (BP)	VC	−9.38	0.21	6,850	90	6,820	90	7,660
TR7 (1)	Tobacco Range	VC	−2.42	0.21	3,050	80	3,020	80	3,230
TR7 (1)	Tobacco Range (BP)	VC	−8.04	0.21	6,570	80	6,540	80	7,440
J (1)	Tobacco Range	VC	−1.50	0.21	3,550	80	3,520	80	3,830
J (1)	Tobacco Range (BP)	VC	−7.19	0.21	5,770	110	5,740	110	6,510
(2)	Boo Bee Patch Reef	VC	−18	0.21	8,780	100	8,747	100	9,703
CB6 (2)	Carrie Bow Cay (BP)	VC	−13.98	0.21	7,619	320	7,590	320	8,390
CB5 (2)	Carrie Bow Cay (BP)	VC	−14.87	0.21	8,237	270	8,200	270	9,130
CB6 (2)	Carrie Bow Cay	VC	−7.00	0.21	6,804	150	6,770	150	7,610
*CB7 (2)	Carrie Bow Cay (BP)	VC	−5.22	0.21	2,861	190	2,830	190	2,940
1A-128-P (3)	Twin Cays	VC	−1.76	0.21	3,655	80	3,622	80	3,951
1A-335-P (3)	Twin Cays	VC	−4.59	0.21	6,065	75	6,032	75	6,867
1A-350-P (3)	Twin Cays (BP)	VC	−4.73	0.21	6,030	105	5,997	105	6,838
1A-420-Wood (3)	Twin Cays	VC	−5.70	0.21	6,240	60	6,307	72	7,250
1A-518-Wood (3)	Twin Cays	VC	−7.02	0.21	7,080	110	7,047	117	7,900
1B-360-P (3)	Twin Cays (BP)	VC	7.06	0.21	6,070	110	6,037	110	6,828
1C-60-P (3)	Twin Cays	VC	−1.77	0.21	2,835	130	2,802	130	2,910
1C-425-P (3)	Twin Cays	VC	−5.76	0.21	5,745	150	5,712	150	6,491
1C-555-P (3)	Twin Cays (BP)	VC	−7.19	0.21	6,040	145	6,007	145	6,852
2-15-P (3)	Twin Cays	VC	−1.55	0.21	3,960	95	3,927	95	4,411
2-210-P (3)	Twin Cays (BP)	VC	−4.25	0.21	5,915	90	5,883	90	6,721
2-204-Wood (3)	Twin Cays	VC	−4.18	0.21	6,050	100	5,567	108	6,372
3-90-P (3)	Twin Cays	VC	−1.53	0.21	3,400	105	3,367	105	3,591
3-260-P (3)	Twin Cays (BP)	VC	−4.50	0.21	6,520	160	6,487	160	7,423
4-55-P (3)	Twin Cays	VC	−1.05	0.21	800	70	767	70	676
6-200-215-P (3)	Twin Cays	VC	−2.31	0.21	2,490	60	2,460	60	2,660
6-620-640-P (3)	Twin Cays (BP)	VC	−6.75	0.21	6,920	110	6,890	110	7,700
7-250-270-P (3)	Twin Cays	VC	−3.30	0.21	5,870	100	5,840	100	6,660
7-500-520-P (3)	Twin Cays	VC	−6.35	0.21	6,310	90	6,280	90	7,240
7-693-713-P (3)	Twin Cays (BP)	VC	−8.71	0.21	6,730	90	6,700	90	7,580
9-200-220-P (3)	Twin Cays	VC	−4.45	0.21	5,210	90	5,180	90	5,920
9-350-370-P (3)	Twin Cays (BP)	VC	−6.43	0.21	5,870	90	5,840	90	6,660
11-190-210-P (3)	Twin Cays (BP)	VC	−3.71	0.21	5,420	70	5,390	70	6,190
15-250-270-P (3)	Twin Cays	VC	−3.08	0.21	4,270	80	4,240	80	4,830
15-500-520-P (3)	Twin Cays	VC	−6.15	0.21	5,670	80	5,640	80	6,410
15-690-709-P (3)	Twin Cays (BP)	VC	−8.49	0.21	6,920	90	6,890	90	7,700
16-630-644-P (3)	Twin Cays (BP)	VC	−8.12	0.21	6,450	90	6,420	90	7,320
Florida Keys									
Sands Cut (4)	Sands Key/Elliot Key	HC	0	0.66	360	60	330	60	380

Table 1 (Contd.)

Core/sample/ ID (ref.)	Locality	Sampling method	Sample elevation (m MSL)	Tide range (m)	^{14}C date (years B.P.)	Range (years)	^{14}C age		Cal BP (calendar years)
							Conventional (years)	Range (years)	
Sands Cut (4)	Sands Key/Elliot Key	HC	−0.5	0.66	1,740	60	1,710	60	1,600
Sands Cut (4)	Sands Key/Elliot Key	HC	−1.00	0.66	2,530	80	2,500	80	2,560
Sands Cut (4)	Sands Key/Elliot Key	HC	−1.50	0.66	2,580	70	2,550	70	2,730
Sands Cut (4)	Sands Key/Elliot Key	HC	−2.00	0.66	3,980	80	3,950	80	4,420
Sands Cut (4)	Sands Key/Elliot Key	HC	−2.50	0.66	4,080	90	4,050	90	4,520
Sands Cut (4)	Sands Key/Elliot Key (BP)	HC	−2.90	0.66	4,160	140	4,130	140	4,620
Broad Creek (4)	Swan Key	HC	−1.00	0.66	2,090	90	2,060	90	2,000
Broad Creek (4)	Swan Key	HC	−1.50	0.66	2,650	90	2,620	90	2,750
Broad Creek (4)	Swan Key	HC	−2.00	0.66	2,850	60	2,820	60	2,920
Broad Creek (4)	Swan Key	HC	−2.50	0.66	3,170	70	3,140	70	3,360
Broad Creek (4)	Swan Key	HC	−3.00	0.66	3,710	70	3,680	70	3,990
Broad Creek (4)	Swan Key	HC	−3.50	0.66	3,970	100	3,940	100	4,410
Broad Creek (4)	Swan Key	HC	−4.00	0.66	4,050	90	4,020	90	4,480
Broad Creek (4)	Swan Key	HC	−4.50	0.66	4,150	150	4,120	150	4,780
Broad Creek (4)	Swan Key (BP)	HC	−4.80	0.66	4,220	80	4,190	80	4,820
Broad Creek (4)	Swan Key (BP)	HC	−4.90	0.66	4,800	100	4,770	100	5,520
Rodriguez Creek (4)	Key Largo	VC	−1.50	0.66	2,460	1	2,430	40	2,410
Rodriguez Creek (4)	Key Largo	VC	−4.30	0.66	5,550	1	5,520	40	6,300
Alligator Reef (4)	Middle Keys	VC	−7.20	0.66	7,595	85	7,560	80	8,380
Alligator Reef (4)	Middle Keys (BP)	VC	−7.40	0.66	8,010	165	7,980	160	8,820
The Quicksands (4)	West Marquesas	E	−6.70	0.66	6,060	60	6,030	60	6,870
Jamaica									
Lu-2032/6 (5)	Negril	Several	−1.15	0.50	3,810	60	3,777	60	4,149
Lu-2043/12 (5)	Negril	Several	−3.00	0.50	3,190	50	3,157	50	3,377
Lu-2033/13 (5)	Negril	Several	−3.15	0.50	4,740	60	4,704	60	5,350
Lu-2041/14 (5)	Negril	Several	−3.35	0.50	5,100	60	5,067	60	5,754
Lu-2044/18 (5)	Negril	Several	−5.00	0.50	4,480	60	4,447	60	5,044
Lu-2034/19 (5)	Negril	Several	−5.45	0.50	6,220	70	6,187	60	7,074
Lu-2045/20 (5)	Negril	Several	−7.00	0.50	5,240	60	5,207	60	5,933
Lu-2046/22 (5)	Negril	Several	−9.00	0.50	5,910	70	5,877	70	6,701
Lu-2047/24 (5)	Negril	Several	−11.00	0.50	6,670	70	6,637	70	7,508
Lu-2184/5 (5)	Black River	Several	−1.20	0.50	3,240	60	3,207	60	3,405
Lu-207810 (5)	Black River	Several	−2.35	0.50	3,890	60	3,857	60	4,252
Lu-2185/11 (5)	Black River	Several	−2.20	0.50	4,180	60	4,147	60	4,673
Lu-2186/15 (5)	Black River	Several	−4.20	0.50	5,680	70	5,647	70	6,436
Lu-2073/23 (5)	Black River	Several	−6.80	0.50	5,950	70	5,917	70	6,730

No systematic offsets for particular labs were used in calibration, since these values are unknown, apart from Beta Analytic, which has no known offset (Darden Hood, personal communication). Lab error multiplier was set at 1. In cases where several calibration curve intercepts occurred, cal BP ages were chosen by referring to the ranked probability distributions for each possible cal BP age and the 1σ (68.3%) confidence intervals.

Results and discussion

Contemporaneous coral growth (offshore) and peat accumulation (onshore) constitute a closely related combination of indices for constraining water depths and sea-level elevations for Caribbean reef and coastal systems. Depth and calibrated-age data for peat and coral samples are shown in Tables 1, 2 and 3, respectively. Peat and coral time–depth plots are treated separately, and then combined to delineate the regional sea-level curve. Problems with particular data are analyzed. Comparisons of the position of sea level determined from this curve with those of previous curves are presented and discussed below.

Holocene sea-level reconstruction from peat data

All peat data are plotted in Fig. 2A, and exhibit a distinct upward trend over time; however, the peat data field occupies several meters of elevation above the base of the data set (indicated by an interpreted trend line). Two dates (2,940 and 2,760 cal BP: Table 1) that plot deeper than the trend line of the data could have been contaminated by younger roots (shifted too young at correct depth) or highly compacted (shifted too deep at correct age). A large number of samples plot higher in

Table 2 Reef-crest *Acropora palmata* age and elevation data from referenced sources [*1–4*: *1* Lightly et al. (1982); *2* Precht et al., unpublished data; *3* Macintyre et al. (1985); *4* Toscano and Lundberg (1998)]. Original ^{14}C dates were calibrated to calendar years (*Cal BP ages*) as described in the text. Sampling method: *1* subsea outcrop or excavation; *2* cored/drilled. *MSL* Mean sea level

Reef (ref.)	Locality	Sampling method	Sample elevation (m MSL)	^{14}C date (years B.P.)	Range (years)	^{14}C age		Cal BP (Calendar years)
						Conventional (years)	Range (years)	
Umbrella Cay (1)	Abaco Reef, Bahamas	2	−7.3	3,580	90	3,981	99	3,980
Umbrella Cay (1)	Abaco Reef, Bahamas	2	−7	3,685	70	4,086	81	4,940
Umbrella Cay (1)	Abaco Reef, Bahamas	2	−6.4	3,795	90	4,195	99	4,285
Umbrella Cay (1)	Abaco Reef, Bahamas	2	−5.5	3,985	90	4,386	99	4,530
Fish Cays (1)	Abaco Reef, Bahamas	2	−6.8	4,515	80	4,916	90	5,270
Vauclin Reef (1)	Martinique	2	−4	1,670	120	2,071	127	1,670
Vauclin Reef (1)	Martinique	2	−1	805	55	1,206	68	750
Vauclin Reef (1)	Martinique	2	−0.9	560	110	961	117	540
Rameville Reef (1)	Martinique	2	−2	1,980	65	2,381	76	2,000
Pinsonelle Algal Ridge (1)	Martinique	2	−4	2,110	120	2,511	127	2,160
Galeta Point (1)	Panama	2	−12.5	6,150	95	6,551	103	7,077
Galeta Point (1)	Panama	2	−12.3	6,500	100	6,901	108	7,420
Galeta Point (1)	Panama	2	−11.5	6,680	110	7,081	117	7,570
Galeta Point (1)	Panama	2	−6.8	5,610	95	6,011	103	6,430
Galeta Point (1)	Panama	2	−6	5,120	65	5,521	65	5,910
Galeta Point (1)	Panama	2	−5.8	4,840	85	5,241	94	5,600
Galeta Point (1)	Panama	2	−5.5	3,535	80	3,936	90	3,910
Galeta Point (1)	Panama	2	−3.8	3,755	85	4,156	94	4,230
Tague Bay, Romney Point (1)	St. Croix, USVI	2	−10.4	6,135	80	6,536	90	7,030
Tague Bay, Romney Point (1)	St. Croix, USVI	2	−7.2	5,490	85	5,891	94	6,300
Tague Bay, Cramer Park (1)	St. Croix, USVI	2	−1.2	720	80	1,121	90	670
Shelf-edge reef, East Point (1)	St. Croix, USVI	2	−23.5	9,075	70	9,476	81	10,270
North Shore Reef (1)	St. Croix, USVI	2	−2.7	1,850	65	2,251	76	1,860
Isaac's Algal Ridge (1)	St. Croix, USVI	2	−8.5	4,040	95	4,441	103	4,610
Hess Channel, shelf edge (1)	St. Croix, USVI	2	−13	7,240	70	7,641	81	8,110
Hess Channel, mid shelf (1)	St. Croix, USVI	2	−3.7	970	95	1,371	103	920
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−17.5	7,740	65	8,141	76	8,600
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−27	8,405	80	8,806	90	9,200
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−23	7,295	70	7,696	70	8,160
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−24	8,900	95	9,301	95	9,920
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−19.5	8,010	80	8,411	90	8,920
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−18	8,295	90	8,696	99	9,070
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−26.5	9,440	85	9,841	94	10,610
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−16.5	7,840	65	8,241	76	8,770
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−20.5	7,595	70	7,996	81	8,420
Lower (15-m) Ridge (1)	Upper Florida Keys	1	−17.5	7,145	80	7,546	90	8,000
Upper Ridge (2)	Upper Florida Keys	1	−7.8	5,950	90	6,351	99	6,800
Upper Ridge (2)	Upper Florida Keys	1	−7.8	6,200	80	6,601	90	7,150
Upper Ridge (2)	Upper Florida Keys	1	−7.9	6,070	60	6,471	72	6,970
Upper Ridge (2)	Upper Florida Keys	1	−8.5	6,360	70	6,761	81	7,270
Upper Ridge (2)	Upper Florida Keys	1	−8.6	6,350	60	6,751	72	7,290
Upper Ridge (2)	Upper Florida Keys	1	−8.7	6,470	90	6,871	99	7,410
Upper Ridge (2)	Upper Florida Keys	1	−8.7	6,520	60	6,921	72	7,420
Upper Ridge (2)	Upper Florida Keys	1	−8.7	6,310	60	6,711	72	7,250
Upper Ridge (2)	Upper Florida Keys	1	−9.5	6,080	60	6,481	72	6,980
Upper Ridge (2)	Upper Florida Keys	1	−9.5	6,240	80	6,641	90	7,200
Bahia Salina Del Sur (1)	Vieques, Puerto Rico	2	−5	2,020	70	2,421	81	2,060
Bahia Salina Del Sur (1)	Vieques, Puerto Rico	2	−2.8	860	90	1,261	99	790
Bahia Salina Del Sur (1)	Vieques, Puerto Rico	2	−2.3	2,155	80	2,556	90	2,270
Nonsuch (3)	Antigua	2	−1.38	670	75	1,071	85	644
Nonsuch (3)	Antigua	2	−3.7	3,710	65	4,111	76	4,150

the section than would be expected if the data set consisted solely of fringing *R. mangle* peats that should form within the intertidal zone. This suggests that the history recorded in peat sections incorporates periodic facies shifts to more elevated environments dominated by species such as *Avicennia*, which occur slightly higher in the tidal cycle (Woodroffe 1995). Several wood samples plot high in the data field along with a number of peat samples that likely originated in supratidal environments. The data indicate a definitive trend over time, as delineated in Fig. 2A, indicating that elements of the long vertical sections of peat (those lowest in elevation in Fig. 2A) do consist of intertidal peats that provide a good upper constraint on sea level.

Table 3 Reef-crest *Acropora palmata* age and elevation data from referenced source (Toscano and Lundberg (1998). TIMS U-Th data are compatible with cal BP ages (see Table 2. Sampling method: *1* subsea outcrop or excavation; *2* cored/drilled. *FL* Florida; *MSL* mean sea level

Sample ID (ref.)	Location	Sampling method	Sampling elevation (m MSL)	TIMS U-Th (years)	Error
Sand Key Outlier Reef	Lower FL Keys Shelf Edge	2	−9.3	6,900	170
Sand Key Outlier Reef	Lower FL Keys Shelf Edge	2	−9.6	6,700	130
Sand Key Outlier Reef	Lower FL Keys Shelf Edge	2	−11.5	8,000	90
Sand Key Outlier Reef	Lower FL Keys Shelf Edge	2	−11.3	8,200	100
Carysfort Outlier Reef	Upper FL Keys Shelf Edge	2	−9.7	7,000	190

Woodroffe's (1995) observation that Tobacco Range mangrove subenvironments cover an elevation range of no more than 15 cm indicates that peats plotting higher than the curve drawn on the plot are not likely due to inaccurate elevations of core sites. More likely, the lack of definitive peat identification has allowed inclusion of a number of samples from slightly more elevated types which are only flooded during extreme spring tides. Certainly, placing a sea-level curve above all peat plots (or even using a mean curve through all peat data) is not reasonable in that this would submerge the majority of true intertidal peat plots by up to 4 m below sea level. If several meters submerge the true intertidal peats, the shallow-water *A. palmata* framework data (introduced next into the plot) would shift accordingly to unacceptably deep (> > 5-m) depths for reef crest framework growth and keep-up in Caribbean waters.

Scholl (1964a, 1964b) used only fibrous basal peats (on shallow bedrock or fresh-water sediment) as sea-level indicators on the southwest Florida shelf; however – that data set does not account for the time/depth range of the reef tract. Florida Keys peat data (Robbin 1984)

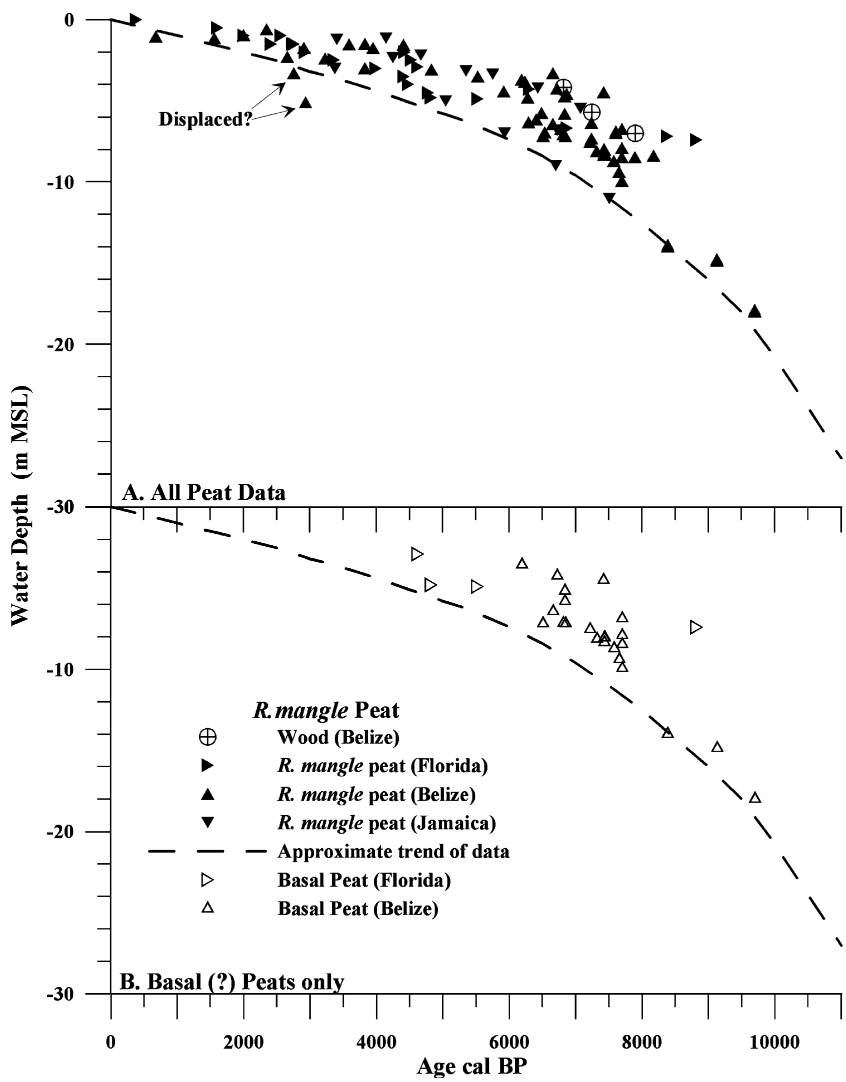

Fig. 2. A Calibrated mangrove peat data from Florida, Belize (Tobacco Range, Twin Cays, and Carrie Bow Cay), and Jamaica in time–depth space. *Dashed line* drawn along base of data field indicates an upward trend over time (but is not a sea-level curve). *Displaced* refers to two samples highlighted in Table 1, which plot deeper than the data field or trend line, due either to compaction or to dating complications such as younger root contamination. **B** Interpreted basal or near-basal peat data from Florida and Belize (as designated in original publications). The past 4 kyr are not represented due to lack of continuous shoreward transect samples. In both cases, variable peat elevations in the data field are due to lack of peat identifications and likelihood of inclusion of mixed species and facies covering a range of possible elevations. Thus, limiting the peat database to only interpreted basal peats (**B**) does not eliminate samples representing more elevated mangrove species and facies. Utilizing the complete database in **A** allows for portions of long vertical sections that do represent intertidal facies to contribute to definition of the sea-level record from 4 kyr ago to the present

taken from vertical sections contain only four possible basal samples; however, at least some of the remaining samples may track sea level up section. Digerfeldt and Hendry (1987) identified only 2 of 55 samples as peat on bedrock; these are not from *R. mangle* facies. If these *inferred* near-basal peats (marked in Table 1) from Belize and Florida sections are plotted (Fig. 2B), the portion of the sea-level curve from ≊4 ka to the present is undocumented, and the basal peat data do not exhibit as clear a trend as does the complete peat data set in Fig. 2A. The full peat data set clearly describes a sea-level trend over time, indicating that elements of the long vertical sections of peat do consist of intertidal peats that provide a good upper constraint on sea level. We therefore utilize all peat samples to cover the full time frame of the Holocene. We regard the peats plotting near the base of the upward-trending data field as consisting of sea-level tracking deposits, and the associated elevated samples as consisting of related species occurring above the intertidal zone.

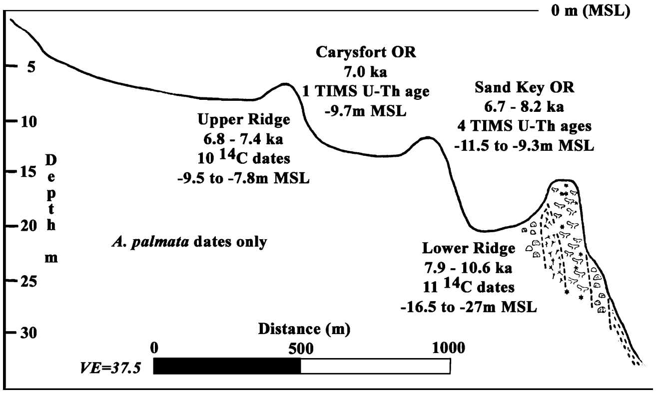

Fig. 3 Cross section showing three shore-parallel reef ridges offshore of Miami, Florida (location 2 in Fig. 1), with calibrated age and elevation ranges. These off-shelf ridges contribute critical early- to mid-Holocene data to the sea-level curve. While the Middle Ridge has not been cored in the Miami area, Middle-Ridge equivalent data were obtained from relict reef sections to the south [Carysfort and Sand Key outlier reefs (*OR*s); Toscano and Lundberg (1998)]. TIMS U-Th ages from *A. palmata* samples indicate that the Holocene portion of Sand Key OR is roughly Middle-Ridge equivalent in age, while the Holocene portion of Carysfort OR overlaps the age ranges of both the Upper and Middle Ridges

Holocene sea-level reconstruction from coral data

The coral data forming the basis of this analysis are taken from the compilation of Lighty et al. (1982), Macintyre et al. (1985), the U-Th data of Toscano and Lundberg (1998), and new ^{14}C dates from east Florida (Precht et al., unpublished data). Coral data from Florida come from several relict geomorphologic features along the reef tract. Lighty et al. (1978) dated *A. palmata* framework from the lowermost of three shore-parallel reef ridges near Miami (Lower, Middle, and Upper ridges; Fig. 3). After calibration, the age range of the Lower ridge spanned 10,600–7,900 cal BP (Tables 2 and 3). TIMS U-Th dates on a total of five *A. palmata* from Carysfort Outlier Reef (one sample) and Sand Key Outlier Reef [four samples; Toscano and Lundberg (1998); Fig. 3] ranged from 8.2–6.7 ka. Ten new ^{14}C dates on *A. palmata* from the Upper ridge (Fig. 3) ranged from 7,400–6,800 cal BP.

Coral data are plotted in Fig. 4 and occupy a depth range of several meters or more below a distinct upper curvature that roughly coincides with the basal curvature of the peat plots (Fig. 2A). This line estimates a minimum sea-level curve for the calibrated coral data field, keeping all coral submerged. For comparison, the original coral-based, minimum sea-level curve of Lighty et al. (1982) is reproduced in Fig. 4 (dashed line). A gap in coral data spans 3.9–2.3 ka. The large depth space of coral data could be related to downward transport (from

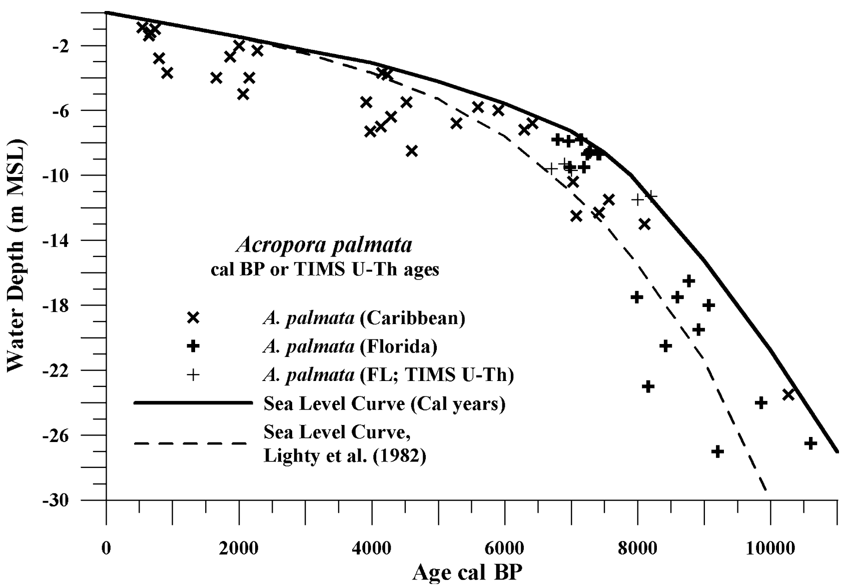

Fig. 4 Calibrated time–depth plot of Caribbean *A. palmata* samples. *Solid line* indicates the minimum sea-level curve required to submerge the coral field. *Dashed line* is the Lighty et al. (1982) minimum sea-level curve (based on uncalibrated ^{14}C data) for comparison. Age and depth data describing the new curve are given in Table 4. Calibrated coral data and references are given in Tables 2 and 3. TIMS U-Th-dated samples from Toscano and Lundberg (1998) have been added and are listed in Table 3

life position) of broken *A. palmata* branches despite efforts to sample only in-place framework, particularly if cored samples were used (Table 2). In addition, *A. palmata* framework might exist below depths of 5 m, especially during periods of more rapid SLR (catch-up mode), as may be interpreted from Fig. 4 in the deepest/oldest part of the data set, or in areas with high water clarity, which allows for light penetration and coral growth at slightly greater depths. The recent glacio-hydro-isostatic simulations of Lambeck et al. (2002) suggest that some of the scatter seen in both the coral and peat fields might be related to differential isostatic adjustments in the range of localities used in this study. Because these corrections have not been specified for the reef sites used in this paper, we have not attempted to adjust the sample elevations. We placed the curve in Fig. 4 to submerge all coral data at their currently known elevations.

Combined coral and peat sea-level curve

When the intertidal *R. mangle* and associated peat data are combined with Caribbean-wide *A. palmata* data, a relatively complete 11-kyr record of regional coral-reef and mangrove accumulation in response to SLR is realized (Fig. 5). The age-calibrated sea-level curve is placed above the coral field in order to keep the uppermost coral shallowly submerged (see Fig. 4 and Table 4). The positioning of the curve based on the coral field also roughly corresponds to the base of the peat data field. The curve is not a mathematical function but a deliberate placement of sea-level elevation that is consistent with the relationship between contemporaneous and locally associated intertidal peat and shallow-water coral growth and their respective depth requirements. A number of peat samples plot on or below the sea-level curve. The deepest of these include four samples from Jamaica and three samples from Belize (Fig. 5). If we lowered the curve to account for the deepest peats, a large number of coral points would be subaerially exposed, which is an untenable scenario. Peats can be compacted naturally (dewatered or decayed) or during coring, contaminated with younger roots, or can accumulate in depressions in karst surfaces and thus plot at anomalously deep depths compared to an idealized transgressive slope. Alternatively, the possibility of differential isostatic histories between sites may have affected the way the samples plot. It should be noted that the inclusion of the full peat database provides sea-level constraints for the period 3.9–2.3 ka, for which no coral data currently are available. The peats conform well to the sea level line drawn to keep the coral submerged, and hence are interpreted to be sea-level tracking deposits.

Due to the progressive increase in sample ages in the calibrated version of Lighty et al.'s (1982) data (Table 2), the calibrated sea-level curve shows a distinct time/depth offset of 1 kyr and 3-m water depth at −27 to −30 m MSL (Table 4), tapering to no offset at −1.5 m

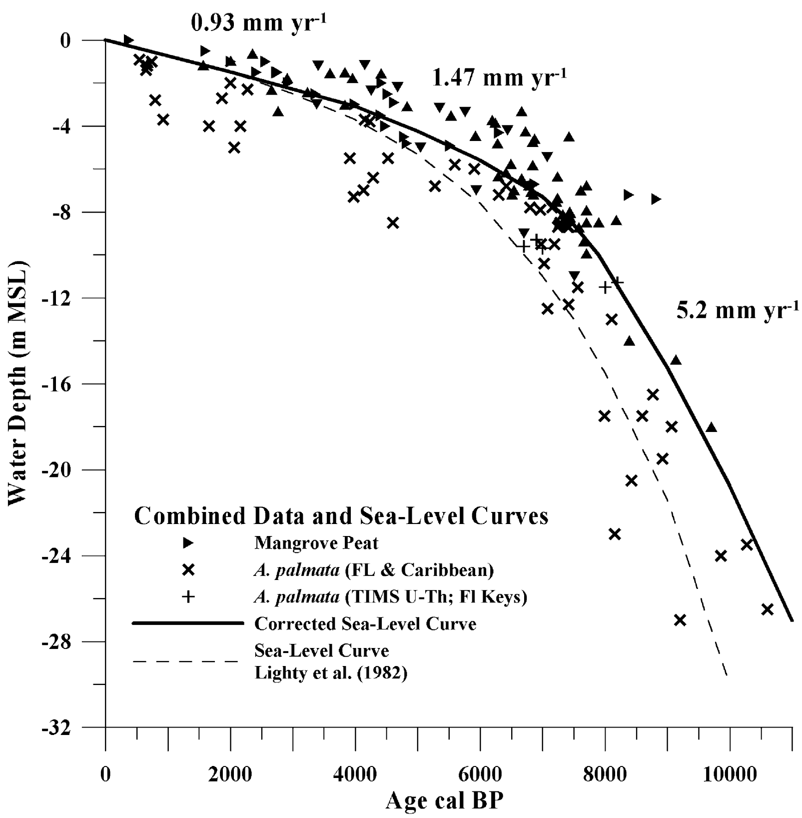

Fig. 5 Combined peat and coral data. The sea-level curve (Table 4) describes a reasonable line of demarcation between intertidal peat data (maximum sea level) and shallow reef crest *A. palmata* data (minimum sea level required to submerge coral). Rates of SLR from the combined coral–peat record range from 5.2 mm yr^{-1} (10.6–7.7 ka), 1.47 mm yr^{-1} (7.7–2 ka), dropping to 0.93 mm yr^{-1} (2–0.4 ka). All rates are well below the maximum accretion rate of *A. palmata* and are not indicative of extreme pulses capable of effecting reef drowning and subsequent backstepping

Table 4 Sea-level curve data. Calibrated curve

Calendar age(years)	Coral–peat sea level(m)
0	0.00
2,000	−1.50
3,000	−2.30
4,000	−3.10
4,500	−3.70
5,000	−4.25
5,500	−4.95
6,000	−5.60
7,000	−7.30
7,500	−8.60
7,900	−10.00
9,000	−15.25
10,000	−20.75
11,000	−27.00

MSL at approximately 2 ka. Thus, for portions of the record older than 2 ka, the timing of sea-level changes between the two curves can differ significantly, so that plotting an uncalibrated dated sample could result in depth errors of several meters and age errors of up to 1 kyr. Lighty et al.'s (1982) original curve lacked coral data for the interval between 6,800 cal BP at −10 m MSL and 5,500 cal BP at −7.3 m MSL. With the addition of TIMS U-Th-dated *A. palmata* data from Carysfort and Sand Key outlier reef sections, constituting Upper and Middle ridge equivalents (Toscano and Lundberg 1998), and *A. palmata* from the Upper reef tract (Precht et al., unpublished data; Fig. 3), the missing interval is accounted for in terms of reef development.

Rates of SLR

Three curve segments and their rates of SLR were calculated from combined peat and coral data (Fig. 5). Calibration of ^{14}C dates adjusted the timing of rate changes from earlier estimates (e.g. Robbin 1984). From 10.6–7.7 ka (previously 14–7 ka B.P.), sea level rose $\approx$5.2 mm yr^{-1}. Robbin's (1984) rate was estimated at 0.3 mm yr^{-1} based on the inclusion of several shelf-edge caliche samples rather than older peat data. The rate of rise then decreased to $\approx$1.47 mm yr^{-1} (previously 1.2 mm yr^{-1}) between 7.7 and 2 ka (previously 7–2 ka B.P.), ending at $\approx$0.93 mm yr^{-1} (previously 0.3 mm yr^{-1}) between 2 and 0.38 ka (previously 2 ka to present). These rates of SLR are very slow (by at least one order of magnitude) with regard to the maximum growth rate of *A. palmata* and its ability to keep pace with rising sea level.

Comparison with Barbados data

Fairbanks (1989) used the Caribbean *A. palmata* database of Lighty et al. (1982) to complete the Barbados record from ~8 ka to the present. In Fig. 6 we plot the absolute age/calibrated version of the Barbados database (Bard et al. 1990) with the calibrated version of the Lighty et al. (1982) database and additional samples from this study (Fig. 5) to assess the matchup between these records. The overlapping sea-level curves (assuming $\approx$2-m water depth in Barbados over *A. palmata*)

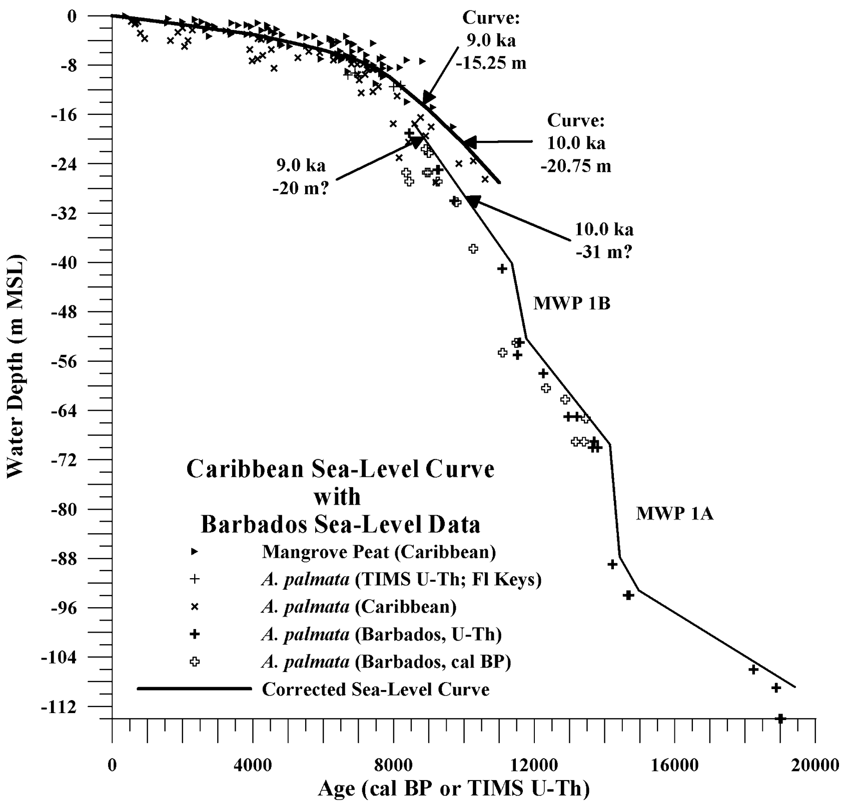

Fig. 6 Data and coral–peat sea-level curve (*thick curved line*) from Fig. 5 combined with *A. palmata* data (cal BP ^{14}C and TIMS U-Th ages) and estimated sea-level curve (*thin line*) from Barbados [cal BP, calculated in this study; U-Th ages, Bard et al. (1990)]. Sample recovery depths of Bard et al. (1990) for Barbados were corrected for the standard 34-cm kyr^{-1} uplift rate to approximate original elevations [as in Fairbanks (1989)]. MWP 1A and MWP 1B refer to periods of very rapid deglacial sea-level rise during which *A. palmata* reefs could not keep pace. Overlap between Caribbean and uplifting Barbados records (from 8.45–11 ka) indicates a progressively larger depth offset over that time frame. This offset is compared at 9.0 ka (4.75 m) and 10.25 ka (10–15 m) in the figure

show a distinct vertical offset (from 8.45–11 ka), suggesting a progressive 4.75 to 10.25-m deepening of sea levels in Barbados (from 9–10 ka) compared with the Caribbean segment (Fig. 6). However, ignoring the sea-level curve lines, there is overlap of the deeper Caribbean *A. palmata* data (four of eleven samples) with the uppermost Barbados data (four of thirteen samples, whose elevations have been corrected for uplift; see Fig. 6).

Barbados corals were cored from deeply submerged continental slope deposits in an area of tectonic uplift. Barbados *A. palmata* samples could have been cored from deeper zones of the paleoreefs, from facies growing in catch-up or give-up depths ($>>5$ m), and not be representative of the shallow reef crest and sea level. Barbados sea-level reconstructions have traditionally factored in an uplift rate of 0.34 mm yr^{-1}, assumed to be constant since the late Pleistocene (Matthews 1973), but which might have been episodic or variable (Fairbanks 1989). Lambeck et al. (2002) used the slowest calculated uplift rate of 0.25 mm yr^{-1}, a difference of 0.11 mm yr^{-1}, which, if more accurate, could amount to an increase in elevation of the Barbados data by up to 1.1 m in the 10-ka range, closing some of the gap. Additionally, as suggested by Lambeck et al. (2002), the elevations of the Caribbean coral and peat data from several localities may be affected by differential isostatic adjustments since the last glacial maximum (LGM), which cannot be accounted for in this compilation, but might slightly adjust the Caribbean (particularly Florida coral) elevations downward.

Interpretation

The newly calibrated coral–peat sea-level curve provides a corrected record of Holocene sea-level changes for the western Atlantic for the last 11 kyrs, and documents the rates of SLR. Differential isostatic adjustments have not been made to elevations of the plotted samples in this analysis, because they have not been quantitatively defined, but should be made as a next refining step by 3-D Earth modelers using the calibrated age data compiled in this study. The combination of peat and coral data allows for a more specific placement of the sea-level curve than with either record alone. We placed our sea-level curve to adhere to the intertidal depth restrictions of *R. mangle* (assumed to comprise the base of the peat field), and to shallowly submerge the coral field in our plots.

Our new corrected curve overlaps the Lighty et al. (1982) curve back to 3 ka, then begins to shift to progressively older ages, resulting in higher sea-level elevations earlier in the record [see also Bard et al. (1990)]. Calibration of Robbin's (1984) Florida Keys peat data pushed the date of flooding of the back-reef or adjacent main shelf in Florida from approximately 8.0 ka B.P. (Robbin 1984) to 8,800 cal BP, during the growth of the Lower and Middle ridges (Fig. 3). Age overlap between adjacent relict reef ridges indicates that they were at least partially contemporaneous, and that the existence of three ridges is not due to reef termination of individual reef ridges and subsequent backstepping from deeper to shallower locations. This also suggests that the separation of the Upper and Middle ridges near Miami is due to localized geologic and environmental conditions that differed somewhat from conditions at Carysfort and Sand Key.

The latest segment of the curve (2,000–400 yrs ago) indicates a rate of sea-level rise (~0.9 mm yr^{-1}) that is half the rates of sea-level rise over the past 100 years determined from high-resolution instrumental records [average ~1.8 mm yr^{-1}; Maul and Martin (1993); Gornitz (1995); Intergovernmental Panel on Climate Change (1996); Peltier (2001); Douglas (2001); among others]. It is not possible from our data to determine the timing of this increased rate of recent sea-level rise, nor identify its causes, given the ~300-year void between our youngest data and the oldest available historical record in the southern United States [since 1846 at Key West, Florida; Maul and Martin (1993)].

Problems with peat data cannot be resolved from the available literature, particularly the need for definitive identification of peats, in order to distinguish intertidal *R. mangle* from more elevated species such as *Avicennia*. While it would be ideal to collect basal intertidal *R. mangle* peat from reef to shore to reconstruct landward transgressive inundation, intertidal peat facies occurring intermittently over time in long cores should also be utilized to track sea level. In this case, the long vertical sections of peat apparently recorded shifting environments, some of which were sea-level tracking, and some of which represented slightly elevated facies, but which were not (or could not be) accurately identified to species or facies level. Because we plotted the complete peat database (Figs. 2A, 5, and 6), we interpret species/facies variability in the peat sections and infer the deeper-plotting peat samples over time as most likely to represent sea-level tracking, intertidal deposits, especially those that constrain sea level across a gap in the coral database. Post-depositional dewatering/compaction may also alter all original elevations to an unknown extent; however, very few occurrences of significant downward displacement occur in this data set. Younger root contamination may move older samples to erroneously younger times, resulting in an apparently too-deep plot for that sample. Again, application of differential isostatic corrections to the elevations in the peat database may resolve some of the offsets from the sea-level curve observed with the uncorrected data set.

The long-term constant uplift rate in Barbados might require some refinement for the LGM to Holocene period. This, in addition to potential model corrections for the Caribbean database, might close the gap between the Barbados and Caribbean records.

Conclusions

It is now common practice to calibrate marine and terrestrial ^{14}C dates to calendar years for direct comparison with each other, for use in paleoclimatic and coral-reef historical studies, and for direct comparison with TIMS U-Th dates. Until now, there has been no temporally corrected sea-level curve available as a reference for these studies. We have now constructed a corrected sea-level curve from calibrated ^{14}C ages and TIMS U-Th dates, for the advancing seas of the Holocene transgression over the past 11 kyr. Comparison of the new calibrated curve with previous versions indicates a progressive shift to older ages from 3 ka back to 11 ka, at which time a 1-kyr increase in calibrated sample age is noted. Future studies in the Caribbean region will now be able to compare calibrated ^{14}C dates with this curve to establish pre-existing water depths, particularly from 3–11 ka, where the offset in age can result in large age, as well as sea-level elevation, errors. When specific and accurate locality-based isostatic elevation corrections can be made available and incorporated into this reconstruction, a more accurate realization of Holocene sea level may be attained. The combination of radiocarbon dates from sea-level tracking coral and intertidal peat deposits delineates past positions of this late Holocene curve more accurately than could be achieved by dating only one type of record. The resulting corrected sea-level curve indicates that the rise in sea level over the last 11 kyrs has never exceeded the maximum accretion rate of *A. palmata* facies; therefore, any actual interruption in growth patterns of this facies (indicated by the curve or by stratigraphic data) would more likely be related to climatic or environmental stress conditions rather than to stranding/drowning by rapid sea-level rise. Mangrove peat studies for sea-level reconstructions will require greater documentation. Future geologic research in mangrove areas must adopt more precise methodologies wherever possible in order to achieve accurate elevation control, stratigraphic and topographic details in areas cored or sampled, ecological and hydrological knowledge of the environment, and unequivocal sample identification.

Acknowledgements We thank Darden Hood, Beta Analytic, Inc., for assistance with ^{14}C calibrations. Some of the fieldwork for this project was supported by the National Museum of Natural History's Caribbean Coral Reef Ecosystem Program (CCRE contribution no. 660). Helpful discussions with Dennis Hubbard and Richard Stumpf clarified several aspects of the study. E. Bard, W.R. Peltier, and one anonymous reviewer provided comments that greatly enhanced the quality and implications of the final paper.

References

Bard E (1988) Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: paleoceanographic implications. Paleoceanography 3:635–645

Bard E (1998) Geochemical and geophysical implications of the radiocarbon calibration. Geochim Cosmochim Acta 62:2025–2038

Bard E, Hamelin B, Fairbanks RG, Zindler A (1990) Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. Nature 345:405–410

Bard E, Hamelin B, Arnold M, Montaggioni L, Cabioch G, Faure G, Rougerie F (1996) Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. Nature 382:241–244

Bard E, Arnold M, Hamelin B, Tisnerat-Laborde N, Cabioch G (1998) Radiocarbon calibration by means of mass spectrometric $^{230}Th/^{234}U$ and ^{14}C ages of corals: an updated database including samples from Barbados, Mururoa, and Tahiti. Radiocarbon 40:1085–1092

Berger A, Loutre MF (1991) Insolation values for climate of the last 10 million years. Quat Sci Rev 10:297–317

Blanchon P (1998) Continuous record of reef growth over the past 14 k.y. on the mid-Pacific island of Tahiti: comment. Geology 26:479

Blanchon P, Shaw J (1995) Reef drowning during the last deglaciation: evidence for catastrophic SLR and ice sheet collapse. Geology 23:4–8

Bloom AL (1967) Pleistocene shorelines: a new test of isostacy. Geol Soc Am Bull 78:1477–1494

Boardman MR, Neumann AC, Rasmussen KA (1988) Holocene sea-level in the Bahamas. In: Mylroie J (ed) Proc 4th Symp on the Geology of the Bahamas, San Salvador, Bahamian Field Station, pp 45–52

Curray JR (1961) Late Quaternary sea level: a discussion. Geol Soc Am Bull 72:1707–1712

Curray JR (1965) Late Quaternary history, continental shelves of the United States. In: Wright HE, Frey DC (eds) The Quaternary of the United States. Princeton University Press, Princeton, pp 723–735

Digerfeldt G, Hendry MD (1987) An 8000 year Holocene sea-level record from Jamaica: implications for interpretation of Caribbean reef and coastal history. Coral Reefs 5:165–169

Douglas BC (2001) Sea level change in the era of the recording tide gauge. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise history and consequences. International Geophysical Series 75 Academic Press, New York, pp 37–62

Ellison AM, Farnsworth EJ (2001) Mangrove communities. In: Bertness MD, Gaines SD, Hay ME (eds) Marine community ecology. Sinauer Associates, Sunderland, Massachusetts, pp 423–442

Ellison J (1993) Mangrove retreat with rising sea level, Bermuda. Estuarine Coastal Shelf Sci 37:75–87

Ellison J, Stoddart DR (1991) Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. J Coastal Res 7:151–165

Enos P (1977) Holocene sediment accumulations of the south Florida shelf margin. In: Enos P, Perkins RD, Quaternary sedimentation in south Florida. Geol Soc Am Mem 147:1–130

Fairbanks RG (1989) A 17,000-year glacio-eustatic sea-level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. Nature 342:637–642

Field CD (1995) Impact of expected climate change on mangroves. Hydrobiologia 295:75–81

Gornitz V (1995) A comparison of differences between recent and late Holocene sea level trends from eastern North America and other selected regions. In: Finkl CW (ed) Holocene cycles: climate, sea levels and sedimentation. J Coastal Res Spec Issue 17:287–297

Graus RR, Macintyre I (1998) Global warming and the future of Caribbean coral reefs. Carbs Evaps 13:43–47

Guilderson TP, Fairbanks RG, Rubenstone JL (1994) Tropical temperature variations since 20,000 years ago: modulating interhemispheric climate change. Science 263:663–665

Halley RB, Shinn EA, Hudson JH, Lidz B (1977) Recent and relict topography of Boo Bee patch reef, Belize. In: Proc 3rd Int Coral Reef Symp, Miami, Florida, Publ 2, pp 29–35

Intergovernmental Panel on Climate Change (1996) Climate change 1995: the science of climate change. Cambridge University Press, Cambridge, 572 pp

Lambeck K, Yokoyama Y, Purcell T (2002) Into and out of the last glacial maximum: sea-level change during oxygen isotope stages 3 and 2. Quat Sci Rev 21:343–360

Lighty RG, Macintyre IG, Stuckenrath R (1978) Submerged early Holocene barrier reef south-east Florida shelf. Nature 275:59–60

Lighty RG, Macintyre IG, Stuckenrath R (1982) *Acropora palmata* reef framework: a reliable indicator of sea-level in the western Atlantic for the past 10,000 years. Coral Reefs 1:125–130

Macintyre IG, Multer HG, Zankl HL, Hubbard DK, Weiss MP, Stuckenrath R (1985) Growth and depositional facies of a windward reef complex (Nonsuch Bay, Antigua, W.I.) Proc 5th Int Coral Reef Congr Tahiti 6:605–610

Macintyre IG, Littler MM, Littler DS (1995) Holocene history of Tobacco Range, Belize, Central America. Atoll Res Bull 430

Macintyre IG, Toscano MA, Lighty RG, Bond GB (2003) Holocene history of the mangrove islands of Twin Cays, Belize, Central America. Atoll Res Bull (in press)

Matthews RK (1973) Relative elevation of Late Pleistocene high sea level stands: Barbados uplift rates and their implications. Quat Res 3:147–153

Maul GA, Martin DM (1993) Sea level rise at Key West, Florida, 1846–1992: America's longest instrument record? Geophys Res Lett 20:1955–1958

Milliman JD, Emery KO (1968) Sea levels during the past 35,000 years. Science 162:1121–1123

Montaggioni L, Bard E (1998) Continuous record of reef growth over the past 14 k.y. on the mid-Pacific island of Tahiti: reply. Geology 26:479–480

Montaggioni L, Cabioch G, Camoinau GF, Bard E, Ribaud-Laurenti A, Faure G, Dejardin P, Recy J (1997) Continuous record of reef growth over the past 14 k.y. on the mid-Pacific island of Tahiti. Geology 25:555–558

Neumann AC (1971) Quaternary sea-level data from Bermuda: Quaternaria 15:41–43

Parkinson RW, DeLaume RD, White JR (1994) Holocene sea-level rise and the fate of mangrove forests within the wider Caribbean region. J Coastal Res 10:1077–1086

Peltier WR (2001) Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise history and consequences. International Geophysical Series 75. Academic Press, New York, pp 65–95

Peltier WR (2002) On eustatic sea level history: Last Glacial Maximum to Holocene. Quat Sci Rev 21:377–396

Redfield AC (1967) Postglacial change in sea level in the western north Atlantic ocean. Science 157:687–691

Robbin DM (1981) Subaerial $CaCO_3$ crust: a tool for timing reef initiation and defining sea-level changes. Proc 4th Int Coral Reef Symp 1:575–579

Robbin DM (1984) A new Holocene sea-level curve for the upper Florida Keys and Florida reef tract. In: Gleason PJ (ed) Environments of south Florida, present and past. Miami Geological Society, pp 437–458

Scholl DW (1964a) Recent sedimentary record in mangrove swamps and rise in sea level over the southwestern coast of Florida: part 1. Mar Geol 1:344–366

Scholl DW (1964b) Recent sedimentary record in mangrove swamps and rise in sea level over the southwestern coast of Florida: part 2. Mar Geol 2:343–364

Scholl DW, Stuiver M (1967) Recent submergence of southern Florida: a comparison with adjacent coasts and other eustatic data. Geol Soc Am Bull 78:437–454

Scholl DW, Craighead FC, Stuiver M (1969) Florida submergence curve revisited: its relation to coastal sedimentation rates. Science 163:562–564

Shinn EA, Hudson JH, Halley RB, Lidz B, Robbin DM, Macintyre IG (1982) Geology and sediment accumulation rates at Carrie Bow Cay, Belize. Smithsonian Contr Mar Sci 12:63–75

Smith BN, Epstein S (1971) Two categories of $^{13}C/^{12}C$ ratios for higher plants. Plant Physiol 47:380–384

Stuiver M, Braziunas TF (1993) Modeling atmospheric ^{14}C influences and ^{14}C ages of marine samples back to 10,000 BC. Radiocarbon 35:137–189

Stuiver M, Reimer PJ (1993) Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35:215–230

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac FG, v. d. Plicht J, Spurk M (1998a) INTCAL98 radiocarbon age calibration 24,000–0 cal BP. Radiocarbon 40:1041–1083

Stuiver M, Reimer PJ, Braziunas TF (1998b) High-precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40:1127–1151

Toscano MA, Lundberg J (1998) Early Holocene sea-level record from submerged fossil reefs on the southeast Florida margin. Geology 26:255–258

Woodroffe CD (1995) Mangrove vegetation of Tobacco Range and nearby mangrove ranges, central Belize barrier reef. Atoll Res Bull 427