Received: 7 November 2018 | Accepted: 7 February 2019
DOI: 10.1002/dep2.62

SPECIAL ISSUE ARTICLE

The Depositional Record
A journal of the International Association of Sedimentologists
Open Access
IAS
WILEY

Holocene tropical reef accretion and lagoon sedimentation: A quantitative approach to the influence of sea-level rise, climate and subsidence (Belize, Maldives, French Polynesia)

Eberhard Gischler[1] | **J. Harold Hudson**[2]

[1]Institut für Geowissenschaften, Goethe-Universität, Frankfurt am Main, Germany
[2]ReefTech Inc., Miami, Florida

Correspondence
Eberhard Gischler, Institut für Geowissenschaften, Goethe-Universität, Frankfurt am Main, Germany.
Email: gischler@em.uni-frankfurt.de

Abstract
Accretion rates of Holocene tropical coral reefs in three areas in the Atlantic, Pacific and Indian Oceans have been quantified in 79 dated core sections in 34 reef cores from Belize, the Maldives and French Polynesia. Holocene vertical reef accretion rate averages 5.05 m/kyr and has decreased during the past 10 kyr. Accretion rates in branched and massive coral facies are statistically similar. Reef accretion rate is positively correlated with the rate of sea-level rise, that is the degree of creation of accommodation space, and with climate as expressed in a Holocene sea surface temperature anomaly. Accommodation space is also created by subsidence, but at a rate one to two orders of magnitude lower than that created by glacio-eustasy (0.04 to 0.16 m/kyr). Lagoonal background sedimentation in adjacent reef lagoons averages 0.89 m/kyr as measured in 72 dated core sections in 28 cores. Lagoonal carbonate sedimentation on top of underlying mangrove peat usually starts after a considerable hiatus of ca 3 kyr on average. The lagoonal background sedimentation rate increased during the Holocene, probably due to deepening. The differences between vertical reef accretion and lagoonal background sedimentation rates are a major factor in the production of the widely known saucer shapes typical of tropical reefs and carbonate platforms, that is the creation of unfilled accommodation space. Reef core recovery, used as a proxy for reef consolidation, and core depth exhibit a statistically negative correlation based on data from 326 core barrels. Recovery and marine cement abundance (average volume 8.6%) also decrease from windward to leeward core positions. These observations are presumably a result of both a decrease in the rate of sea-level rise that is the increase in time available for submarine cementation during the Holocene and the amount of flushing of reef interstices by marine waters.

KEYWORDS
Belize, French Polynesia, Holocene, lagoon, Maldives, reef

1 | INTRODUCTION

Reef accretion rate has been a geoscience focus, especially in sedimentology and sequence stratigraphy, since the classic paper by Schlager (1981) on reef and carbonate platform drowning, a common phenomenon observed throughout Earth history with the potential to produce sequence boundaries. For the Holocene, Neumann and Macintyre (1985) have discussed the response of tropical coral reefs to rising sea-levels in terms of give-up (drowned), catch-up and keep-up types. Each reef type is characterized by specific coral compositions and successions. Reefs with an abundance of branched corals, usually characteristic of keep-up and the late stages of catch-up types, were supposed to accrete faster than those dominated by massive corals, which may be typical of give-up or early catch-up type reefs (Davies & Marshall, 1980; Neumann & Macintyre, 1985). However, Gischler (2008) and Hubbard (2009) have shown for the Caribbean realm that the accretion rates of reefs predominately constructed of either massive or branched corals are statistically similar. As yet, such statistical comparisons for the Indo-Pacific realm are lacking. Drilling in Holocene reefs, the modern counterparts of the fossil record, has generated an increasing body of data with Dullo (2005) and Montaggioni (2005) providing useful compilations of reef accretion and coral growth rates. Potential growth rates of Scleractinian corals and tropical coral reefs are in the range of rates of rise of glacio-eustatic sea-level. Still, major drilling projects in post-glacial (ca 20 to 10 kyr BP) reefs of Barbados, Tahiti and the Great Barrier Reef have shown that reefs do experience drowning and backstepping during periods of very rapid sea-level rise such as during meltwater pulses (Camoin et al., 2012; Fairbanks, 1989; Webster et al., 2018). In addition, because of deteriorating environmental conditions, for example elevated nutrient input and turbidity, hyperthermal events or diseases, the growth potential of reef builders and reef systems may decrease significantly. Holocene reef accretion has become increasingly important both scientifically and socio-economically in the context of the recent decline of tropical coral reefs due to warming and bleaching (Hughes et al., 2017; Pandolfi, Connolly, Marshall, & Cohen, 2011; Pandolfi et al., 2003), ocean acidification (Eyre et al., 2018; Kleypas et al., 1999) and sea-level rise (Intergovernmental Panel on Climate Change; Hubbard et al., 2014; IPCC, 2013; Pala, 2014; Woodruff, Irish, & Camargo, 2013).

Tropical coral reefs accrete due to a complex interplay of simultaneous processes (Scoffin, 1992). The collective carbonate production of organisms such as reef corals, molluscs, foraminifera and other invertebrates, and calcareous algae leads to reef construction. At the same time, destructive processes both biologically (via bioerosion) and physically (via cyclones) counteract reef construction. Reef sediments are produced, redeposited and distributed in the reef system, and considerable quantities are exported. Early submarine cementation plays an important role in reef consolidation. Still, studies which have quantified all of these processes are extremely rare (Hubbard, Miller, & Scaturo, 1990). Therefore, more data are necessary to constrain our understanding of reef accretion and the possible controlling factors, and to make extrapolations into the near future (Camoin & Webster, 2015). Reef accretion rates have been summarized earlier (Dullo, 2005; Montaggioni, 2005); however, they have not been statistically analysed or quantitatively compared with controlling environmental factors. For these reasons, vertical accretion-rate data from three prominent tropical reef systems in the Atlantic, Pacific and Indian Oceans has been compiled and analysed, and statistically compared with sea-level and climate proxy data.

2 | STUDY AREAS AND METHODS

Data on reef accretion from 34 cores extracted with a wire-line rotary drill system and 1.5-m long core barrels have been compiled and quantitatively analysed in three regions during this study (Figure 1; Table S1). These include the Belize barrier and atoll reefs (western Atlantic), Rasdhoo Atoll in

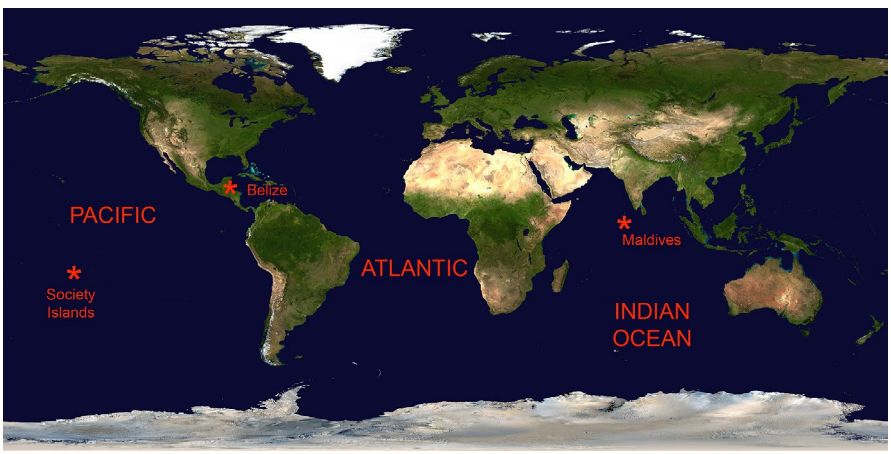

FIGURE 1 Map indicating the locations of the three regions studied

the central Maldives (western Indian Ocean) and the oceanic barrier reef system of Bora Bora in the Society Islands (south Pacific). From Belize, 11 rotary cores drilled on the barrier reef and five rotary cores taken on the offshore atolls have been included (Gischler, 2008). From the Maldives, data from four rotary cores collected on the reef were analysed (Gischler, Hudson, & Pisera, 2008) and included with data from 14 rotary cores from the barrier and fringing reefs of Bora Bora (Gischler et al., 2016, 2019). In Belize and Bora Bora, core traverses were drilled in order to obtain two-dimensional sections of reef architecture. Individual Holocene reef core penetration is up to 31.5 m (average 12.6 m; total 503.5 m). Cores are composed in decreasing abundance of both branched and massive coral, grainstone to rudstone, and unconsolidated sand facies (Gischler, 2008; Gischler et al., 2008, 2016, 2019). Branched coral facies are dominated by acroporids; massive corals by *Orbicella* (Atlantic) and *Porites* (Indo-Pacific). Microbialite facies occur usually in sections older than 6 kyr (Figure 2). Core recovery ranged from 0% to 100% and averaged 27.2% (Table S2). Absolute age data include calibrated radiocarbon and U/Th ages from corals. Ideally, corals for dating were selected utilising shallow-water acroporids with the sampling distances between corals kept more or less equal and averaging 3 to 4 m. The elevation of samples has been reported relative to mean sea-level. Elevation (D) and elevation error ($\pm D$) were calculated based on recovery in individual core barrels (Figure 3) using the formulas:

$$D = \left(2d_{\mathrm{m}} + 1.5 - r\right)/2 \quad (1)$$

$$\pm D = \left(2d_{\mathrm{m}} + 1.5 - r\right)/2 - d_{\mathrm{m}} \quad (2)$$

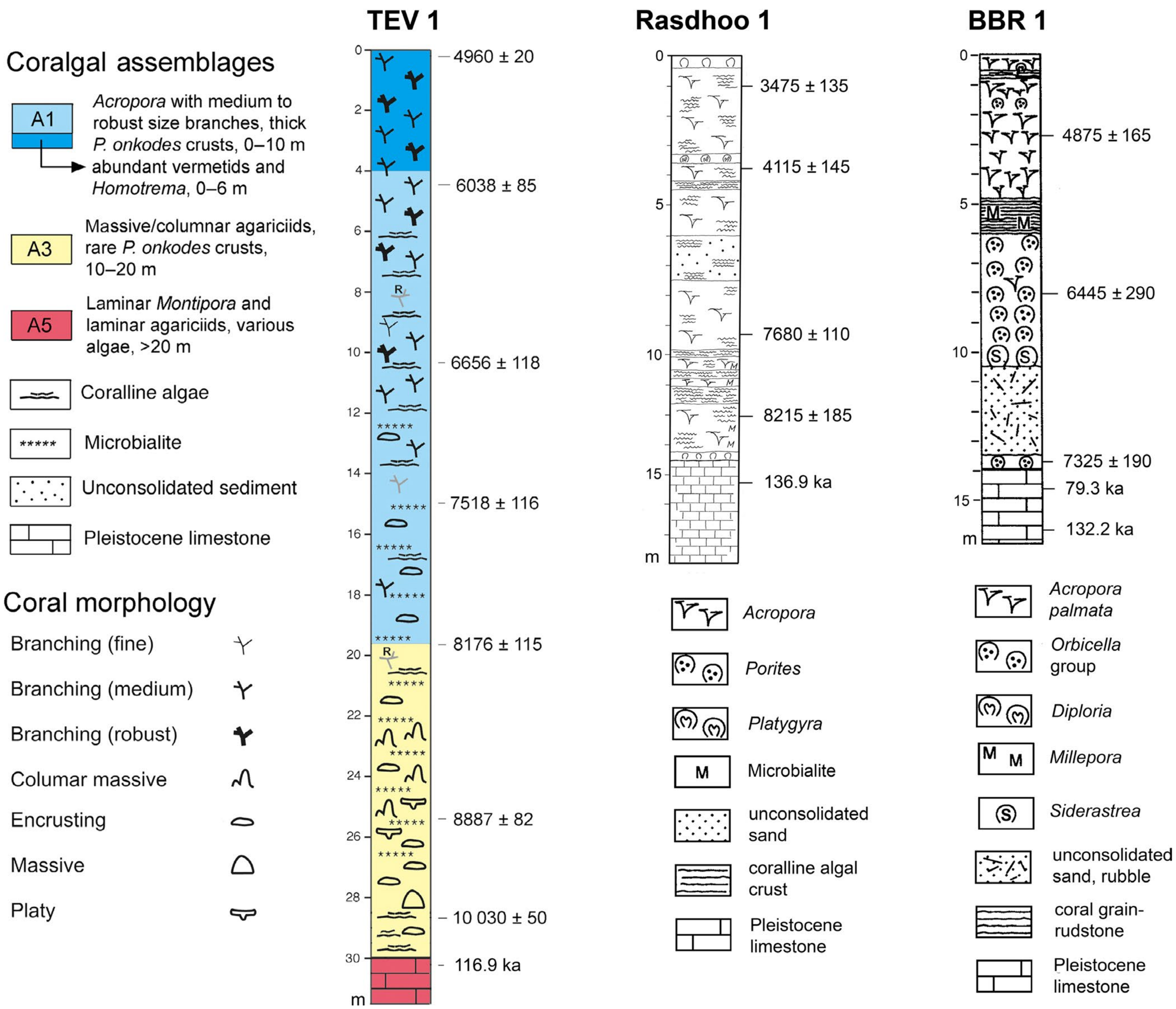

FIGURE 2 Representative rotary core logs from the three regions investigated (modified from Gischler, 2008; Gischler et al., 2008, 2016). TEV 1 from Bora Bora; Rasdhoo 1 from the Maldives; BBR 1 from Belize. Note that there are individual legends for the three core logs

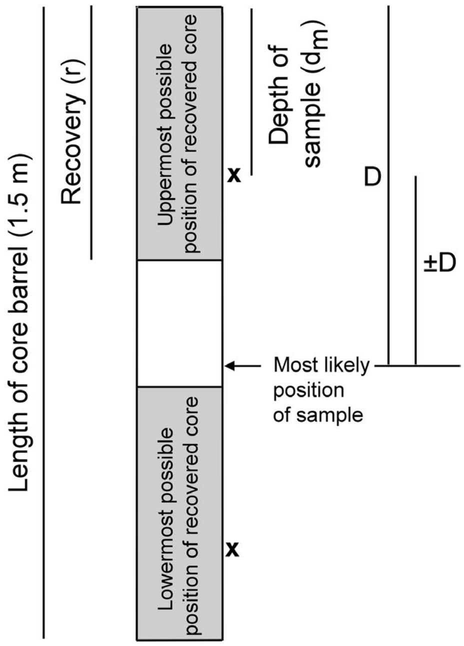

FIGURE 3 Schematic drawing of core barrel to illustrate how sample elevation is calculated in the case of less than 100% recovery during rotary drilling

where d_m is the measured depth in barrel in metres and r is the recovery in %.

Seventy-nine vertical accretion rates were calculated by dividing in core absolute age data by the vertical reef thickness between data points. To compare reefal accretion with adjacent lagoonal background sedimentation, 72 sedimentation rates in adjacent lagoons were calculated by dividing absolute age data (radiocarbon method) by measured distance between age data points in 28 vibracores. Vibracore thickness and sample elevation were corrected for compaction (Table S1); recovery in all vibracores is 100%. Vibracores include 11 cores from Belize atoll lagoons (Gischler, 2003; Schultz, Gischler, & Oschmann, 2010), 11 cores from the lagoon at Rasdhoo Atoll (Klostermann & Gischler, 2015) and 6 cores from the Bora Bora lagoon (Isaack et al., 2016). Individual lagoon cores are up to 6 m long (average 3.8 m; total 111.5 m) and largely comprise packstone, wackestone and mudstone with abundant mollusc, foraminifer and *Halimeda* remains (Figure 4). Ideal successions contain basal soil, mangrove peat, shell-rich beds and carbonate sediments indicative of deepening upward (Gischler, 2003; Isaack et al., 2016; Klostermann & Gischler, 2015). In both calculated reef

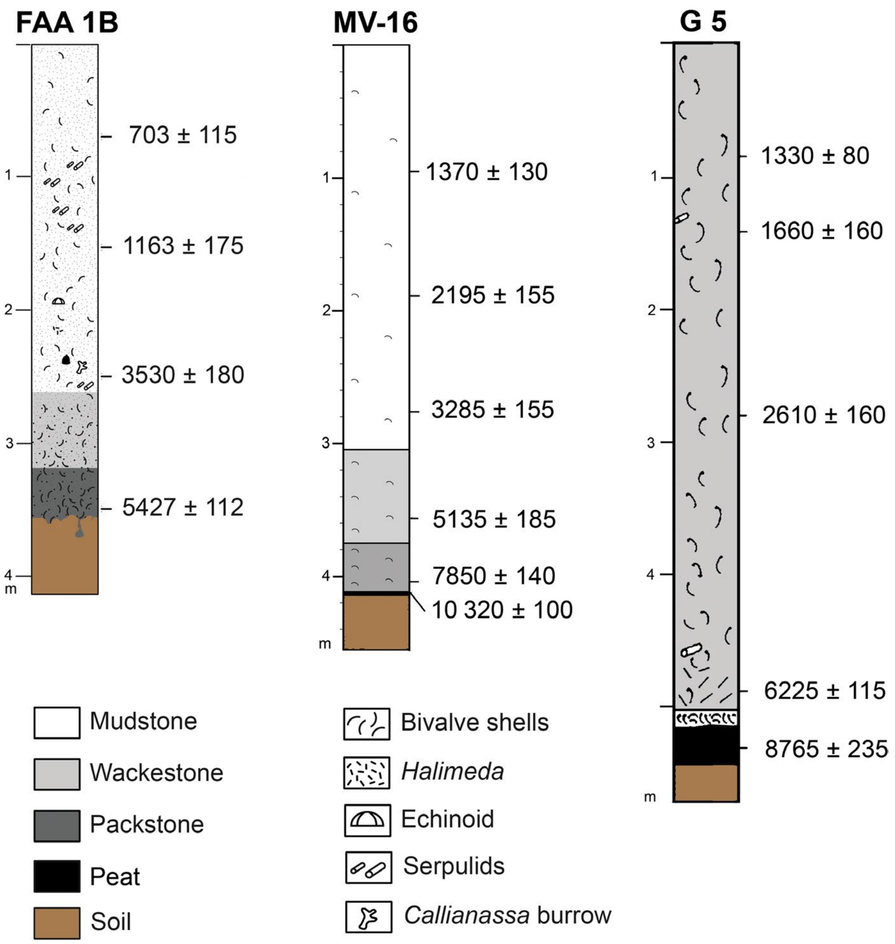

FIGURE 4 Representative vibracore logs from the three regions investigated (modified from Gischler, 2003; Klostermann & Gischler, 2015; Isaack et al., 2016). FAA 1B from Bora Bora; MV-16 from the Maldives; G 5 from Belize. Absolute age data in years

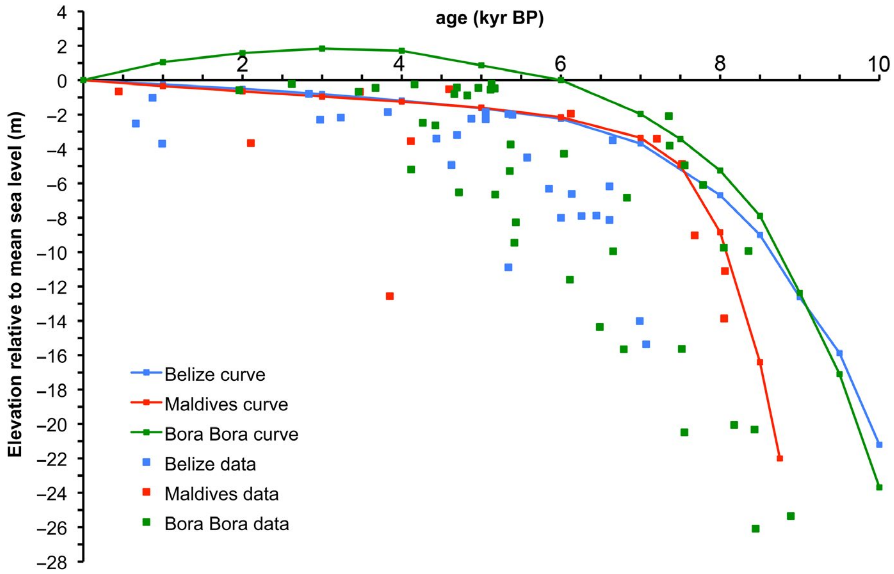

FIGURE 5 Elevation and age data (n = 79) used in this study and regional sea-level curves. Elevation data have been corrected for minimum subsidence

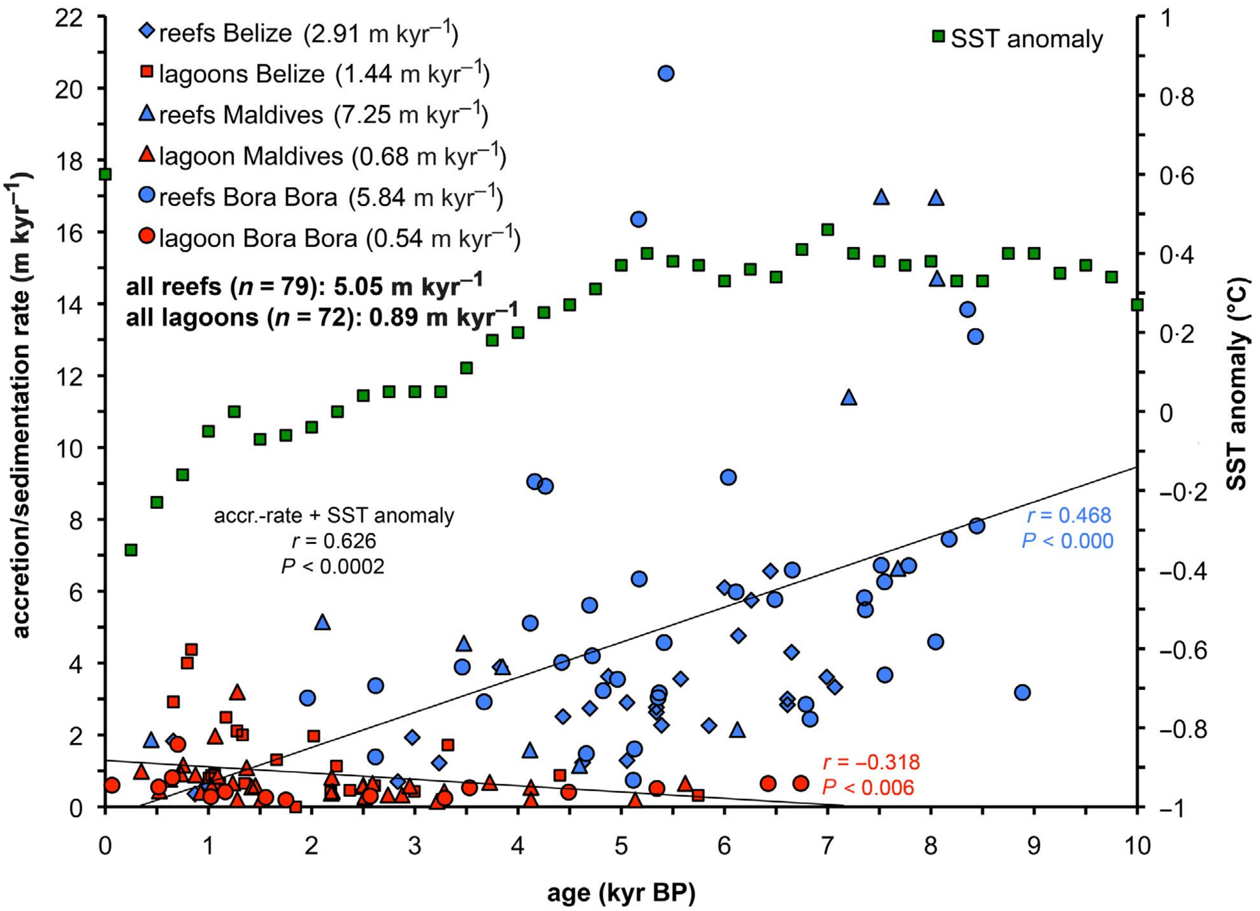

FIGURE 6 Vertical reef accretion and lagoon sedimentation rates from Belize, the Maldives and Bora Bora including regression lines as well as the Holocene climate (SST) anomaly of Marcott et al. (2013). Note that reef accretion rates decrease and lagoonal sedimentation rates increase during the Holocene. Both trends are statistically significant. Average values in upper left corner. Note that modern SST anomaly increases significantly. SST: sea surface temperature

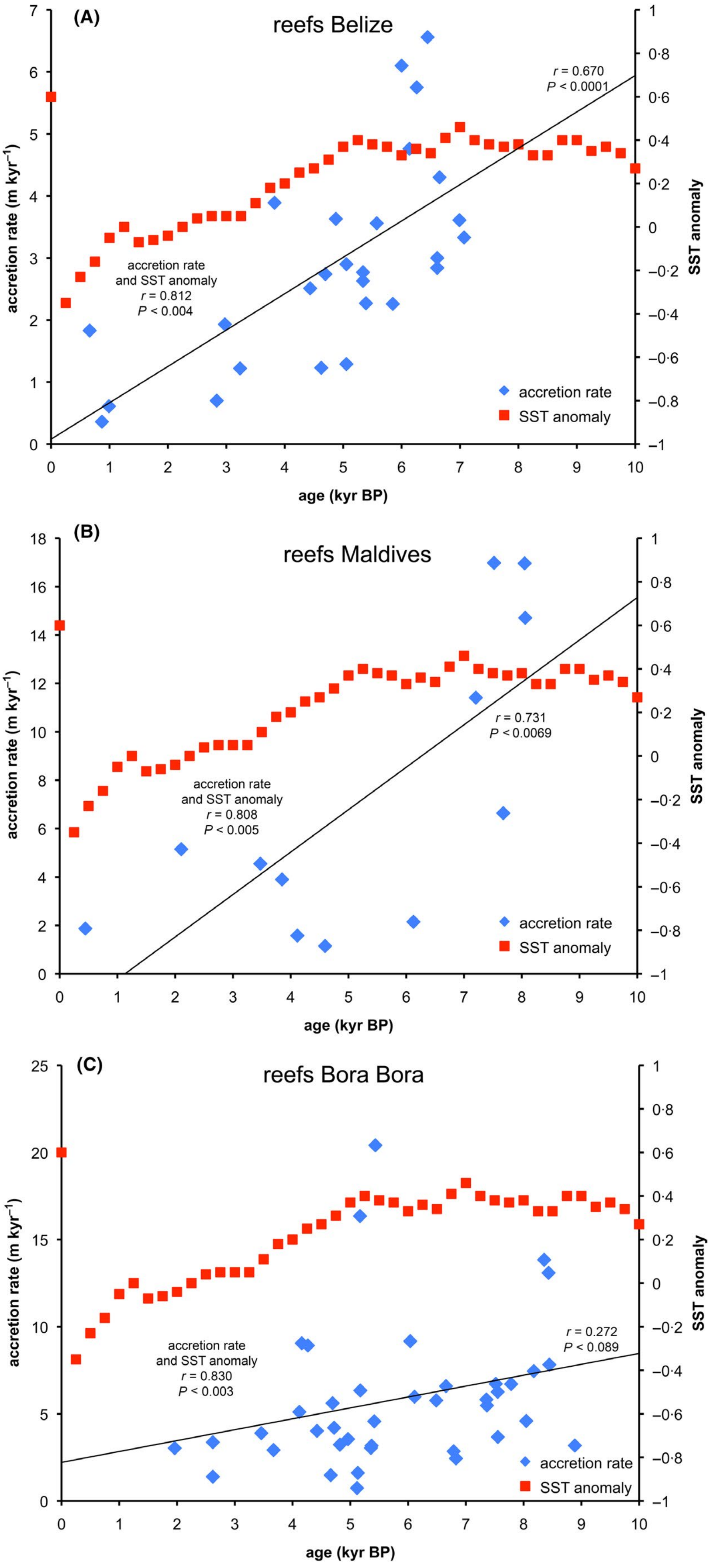

FIGURE 7 Individual vertical reef accretion rates during the Holocene including regression lines

TABLE 1 Reef accretion rate and lagoonal sedimentation rate data from Belize, the Maldives and Bora Bora

Sample	Core depth in m	Error ±	Age kyr cal BP	Error ±	Accr.-rate/ sed-rate m/kyr	Linear error propagation ±	Massive branched facies
Belize reef cores							
BBR 1	2.43	0.5	4.875	0.165	3.63	1.18	M
BBR 1	8.13	0.15	6.445	0.290	6.56	3.75	M
BBR 1	13.9	0.00	7.325	0.190			
BBR 2	2.05	0.15	5.055	0.215	1.29	0.74	B
BBR 2	4.14	0.30	6.675	0.370			
BBR 3	3.76	0.53	6.650	0.190	4.30	3.04	B
BBR 3	8.3	0.53	7.705	0.310			
BBR 4	2.3	0.45	3.235	0.165	1.22	0.45	B
BBR 4	6.43	0.43	6.610	0.360	3.00	1.34	B
BBR 4	11.04	0.40	8.148	0.052			
BBR 5	3.74	0.65	0.990	0.110	0.61	0.29	M
BBR 5	6.86	0.60	6.135	0.310	4.76	2.59	M
BBR 5	14.12	0.35	7.660	0.320			
BBR 6	3.57	0.50	4.435	0.185	2.51	0.84	B
BBR 6	8.15	0.45	6.259	0.048	5.75	1.57	B
BBR 6	12.2	0.00	6.963	0.066			
BBR 7	3.38	0.38	4.695	0.165	2.74	1.78	B
BBR 7	6.54	0.30	5.850	0.340	2.26	2.07	M
BBR 7	8.47	0.50	6.705	0.089			
BBR 8	2.42	0.55	2.975	0.195	1.93	0.75	B
BBR 8	8.25	0.70	6.000	0.340	6.10	5.79	B
BBR 8	14.29	0.64	6.990	0.380	3.61	2.71	M
BBR 8	18.88	0.63	8.260	0.220			
BBR 9	2.55	0.40	0.660	0.100	1.83	0.41	B
BBR 9	11.1	0.55	5.340	0.420	2.63	1.72	M
BBR 9	15.65	0.43	7.070	0.340	3.33	3.08	M
BBB 9	18.88	0.63	8.040	0.240			
BBR 10	2.24	0.60	5.390	0.180	2.27	0.82	B
BBR 10	6.93	0.23	7.460	0.200			
BBR 11	2.18	0.53	5.340	0.210	2.77	1.51	B
BBR 11	6.77	0.53	6.995	0.310			
GR 1	0.91	0.29	2.835	0.135	0.70	0.52	B
GR 1	2.47	0.46	5.055	0.435	2.90	1.7	B
GR 1	8.25	0.73	7.045	0.340			
GR 2	4.72	0.14	5.575	0.135	3.56	2.51	M
GR 2	8.4	0.54	6.610	0.405	2.84	2.33	M
GR 2	11.74	0.26	7.785	0.275			
LR 7	2	0.10	3.825	0.135	3.89	2.64	M
LR 7	5.11	0.05	4.625	0.370	1.23	0.37	M
LR 7	7.9	0.00	6.885	0.270			
TR 4	1.05	0.10	0.870	0.080	0.36	0.18	B
TR 4	2.53	0.48	5.035	0.435			

(Continues)

TABLE 1 (Continued)

Sample	Core depth in m	Error ±	Age kyr cal BP	Error ±	Accr.-rate/ sed-rate m/kyr	Linear error propagation ±	Massive branched facies
Belize lagoon cores							
T4	0.8	0.00	0.660	0.050	2.92	1.26	
T4	1.88	0.00	1.030	0.110	0.88	0.08	
T4	4	0.00	3.445	0.115			
T6	1.18	0.00	0.835	0.105	4.38	2.14	
T6	2.89	0.00	1.225	0.085			
T7	0.66	0.00	0.795	0.155	4.00	2.17	
T7	2.58	0.00	1.275	0.105	2.11	0.58	
T7	4.5	0.00	2.185	0.145	0.42	0.06	
T7	5.43	0.00	4.380	0.150			
L1	1.18	0.00	1.350	0.110	0.65	0.07	
L1	2.73	0.00	3.750	0.150			
L4	0.49	0.00	1.110	0.140	0.64	0.04	
L4	2.77	0.00	4.690	0.080			
L5	0.6	0.00	1.060	0.100	0.63	0.11	
L5	1.34	0.00	2.240	0.110	1.13	0.27	
L5	2.56	0.00	3.320	0.150	1.72	1.13	
L5	3.47	0.00	3.850	0.200			
L6	1.35	0.00	1.005	0.115	0.80	0.17	
L6	2.28	0.00	2.170	0.130			
G2	0.41	0.00	1.170	0.120	2.49	0.87	
G2	2.09	0.00	1.845	0.115	0.97	0.15	
G2	3.76	0.00	3.570	0.150			
G4	0.76	0.00	2.995	0.145	0.43	0.08	
G4	1.37	0.00	4.405	0.125	0.88	0.18	
G4	2.55	0.00	5.745	0.155	0.32	0.02	
G4	3.39	0.00	8.385	0.035			
G5	0.84	0.00	1.330	0.080	2.00	1.45	
G5	1.5	0.00	1.660	0.160	1.31	0.44	
G5	2.74	0.00	2.610	0.160	0.59	0.05	
G5	4.88	0.00	6.225	0.115			
G7	0.48	0.00	1.060	0.100	0.94	0.21	
G7	1.38	0.00	2.020	0.120	1.97	1.13	
G7	2.07	0.00	2.370	0.080	0.46	0.05	
G7	3.23	0.00	4.675	0.165			
Maldives reef cores							
Rasdhoo 1	0.85	0.45	3.475	0.135	4.55	3.36	B
Rasdhoo 1	3.76	0.43	4.115	0.145	1.58	0.32	B
Rasdhoo 1	9.4	0.30	7.680	0.110	6.64	5.27	B
Rasdhoo 1	12.95	0.56	8.215	0.185			
Rasdhoo 2	0.75	0.45	4.595	0.185	1.15	0.58	B
Rasdhoo 2	3.76	0.68	7.205	0.145	11.41	5.4	B
Rasdhoo 2	11.5	0.50	8.060	0.120	14.71	10.95	B

(Continues)

TABLE 1 (Continued)

Sample	Core depth in m	Error ±	Age kyr cal BP	Error ±	Accr.-rate/ sed-rate m/kyr	Linear error propagation ±	Massive branched facies
Rasdhoo 2	18.78	0.73	8.555	0.165			
Rasdhoo 4	2.26	0.68	6.125	0.145	2.15	1.27	B
Rasdhoo 4	5.26	0.56	7.520	0.100	16.98	9.71	B
Rasdhoo 4	14.26	0.68	8.050	0.130	16.96	16.15	B
Rasdhoo 4	20.28	0.73	8.405	0.125			
Rasdhoo 3	0.68	0.40	0.445	0.075	1.87	0.91	B
Rasdhoo 3	3.78	0.65	2.105	0.175	5.15	1.58	M
Rasdhoo 3	12.76	0.53	3.850	0.130	3.90	1.34	M
Rasdhoo 3	18.98	0.53	5.445	0.145			
Maldives lagoon cores							
16	0.98	0.00	1.370	0.130	1.09	0.38	
16	1.88	0.00	2.195	0.155	0.82	0.23	
16	2.77	0.00	3.285	0.155	0.43	0.08	
16	3.57	0.00	5.135	0.185	0.19	0.02	
16	4.08	0.00	7.850	0.140			
19	0.98	0.00	1.090	0.160	0.85	0.21	
19	2.17	0.00	2.495	0.195	0.56	0.28	
19	2.57	0.00	3.215	0.165	0.15	0.01	
19	3.18	0.00	7.375	0.135			
34	0.75	0.00	1.235	0.125	0.66	0.14	
34	1.65	0.00	2.590	0.170	0.65	0.16	
34	2.65	0.00	4.125	0.205	0.54	0.12	
34	3.45	0.00	5.620	0.140	0.65	0.23	
34	4	0.00	6.465	0.165			
12	0.21	0.00	1.280	0.120	3.20	1.3	
12	2.42	0.00	1.970	0.160			
8	0.25	0.00	0.525	0.105	0.44	0.12	
8	0.66	0.00	1.455	0.155	0.59	0.2	
8	1.28	0.00	2.500	0.190	0.60	0.51	
8	1.55	0.00	2.950	0.190	0.58	0.4	
8	1.83	0.00	3.435	0.145			
13	0.17	0.00	0.350	0.120	0.99	0.63	
13	0.55	0.00	0.735	0.125	0.91	0.77	
13	0.85	0.00	1.065	0.155	1.97	1.61	
13	1.6	0.00	1.445	0.155			
29	0.15	0.00	0.755	0.135	1.16	0.56	
29	0.76	0.00	1.280	0.120	0.20	0.06	
29	0.94	0.00	2.190	0.150	0.38	0.19	
29	1.15	0.00	2.740	0.130	0.33	0.13	
29	1.39	0.00	3.460	0.150			
18	0.25	0.00	0.875	0.155	0.89	0.1	
18	2.78	0.00	3.725	0.175	0.68	0.64	
18	3.05	0.00	4.125	0.205	0.20	0.05	

(Continues)

TABLE 1 (Continued)

Sample	Core depth in m	Error ±	Age kyr cal BP	Error ±	Accr.-rate/ sed-rate m/kyr	Linear error propagation ±	Massive branched facies
18	3.34	0.00	5.540	0.120			
24	0.22	0.00	0.625	0.105	0.77	0.64	
24	0.45	0.00	0.925	0.145	0.40	0.23	
24	0.65	0.00	1.420	0.140	0.55	0.2	
24	1.08	0.00	2.200	0.150	0.43	0.19	
24	1.41	0.00	2.965	0.195			
31	0.35	0.00	1.510	0.170	0.20	0.07	
31	0.55	0.00	2.515	0.195	0.28	0.27	
31	0.65	0.00	2.875	0.155	0.33	0.1	
31	1.05	0.00	4.085	0.195			
26	0.48	0.00	1.030	0.140	0.57	0.07	
26	1.9	0.00	3.525	0.165			
Bora Bora reef cores							
TEV 1	0.45	0.45	4.963	0.023	3.55	0.99	B
TEV 1	4.28	0.23	6.038	0.085	9.17	4.07	B
TEV 1	9.95	0.45	6.656	0.118	6.59	3.04	B
TEV 1	15.63	0.63	7.518	0.116	6.72	4.15	B
TEV 1	20.05	0.55	8.176	0.115	7.45	3.05	M
TEV 1	25.35	0.15	8.887	0.082	3.18	1.44	M
TEV 1	28.98	0.48	10.030	0.050			
TEV 2	0.2	0.20	2.618	0.018	1.39	0.49	B
TEV 2	2.48	0.53	4.265	0.043	8.92	3.85	B
TEV 2	6.53	0.53	4.719	0.034	4.20	1.67	B
TEV 2	9.45	0.45	5.415	0.009	4.57	1.33	B
TEV 2	14.35	0.65	6.488	0.062	5.77	1.87	B
TEV 2	20.48	0.53	7.551	0.079	6.26	2.37	M
TEV 2	26.08	0.58	8.446	0.083	7.82	4.39	M
TEV 2	30.88	0.63	9.063	0.110			
TEV 3	0.25	0.25	4.161	0.028	9.05	5.07	B
TEV 3	2.63	0.38	4.423	0.049	4.02	2.18	B
TEV 3	6.65	0.65	5.174	0.064	6.34	1.85	B
TEV 3	11.6	0.40	6.112	0.066	5.98	3.36	B
TEV 3	15.65	0.65	6.789	0.139	2.85	1.08	M
TEV 3	20.33	0.38	8.432	0.125	13.09	8.99	M
TEV 3	24.78	0.28	8.772	0.058			
FAA 1	0.2	0.20	5.128	0.024	1.61	0.35	B
FAA 1	3.8	0.45	7.365	0.057	5.48	2.87	B
FAA 1	6.1	0.10	7.785	0.063	6.71	2.53	B
FAA 1	9.93	0.58	8.356	0.051	13.84	6.17	M
FAA 1	15.8	0.70	8.782	0.047			
FAA 2	0.58	0.58	1.960	0.018	3.03	0.69	M
FAA 2	6.8	0.70	4.012	0.027			
FAA 3	0.88	0.63	4.824	0.037	3.23	0.63	M

(Continues)

TABLE 1 (Continued)

Sample	Core depth in m	Error ±	Age kyr cal BP	Error ±	Accr.-rate/ sed-rate m/kyr	Linear error propagation ±	Massive branched facies
FAA 3	9.75	0.75	7.562	0.070			
Puhia 1	0.55	0.36	5.116	0.027	0.74	0.22	B
Puhia 1	2.09	0.09	7.356	0.037	5.82	3.72	B
Puhia 1	3.54	0.34	7.607	0.050			
Puhia 2	0.81	0.63	4.661	0.026	1.48	0.32	B
Puhia 2	4.94	0.19	7.554	0.043	3.67	0.92	B
Puhia 2	7.91	0.26	8.374	0.042			
Puhia 3	6.84	0.59	6.829	0.036	2.44	1.2	B
Puhia 3	9.75	0.50	8.046	0.117	4.59	2.77	B
Puhia 3	12.71	0.54	8.697	0.051			
Ome 1	0.23	0.07	2.620	0.011	3.37	0.39	B
Ome 1	5.2	0.40	4.118	0.025	5.11	1.32	B
Ome 1	9.85	0.55	5.035	0.026			
Ome 2	0.68	0.43	3.459	0.014	3.89	0.58	B
Ome 2	8.26	0.51	5.434	0.041	20.41	5.69	B
Ome 2	19.64	1.37	5.993	0.023			
Tofari 1	0.45	0.45	3.671	0.017	2.92	0.65	B
Tofari 1	5.29	0.54	5.357	0.027	3.04	0.84	B
Tofari 1	9.75	0.64	6.849	0.030			
Tofari 2	0.43	0.35	4.693	0.019	5.61	0.92	B
Tofari 2	8.26	0.64	6.104	0.036			
Tofari 3	0.48	0.48	5.168	0.020	16.35	10.15	B
Tofari 3	3.74	0.54	5.368	0.042	3.17	1.51	B
Tofari 3	6.75	0.69	6.332	0.030			
Bora Bora lagoon cores							
APO 2	0.37	0.00	0.518	0.038	0.55	0.08	
APO 2	1.5	0.00	2.568	0.255	0.30	0.05	
APO 2	2.07	0.00	4.490	0.085	0.41	0.05	
APO 2	3.0	0.00	6.740	0.180	0.65	0.1	
APO 2	4.3	0.00	8.725	0.135			
APO 3	0.42	0.00	0.065	0.065	0.60	0.15	
APO 3	1.0	0.00	1.023	0.175	0.28	0.02	
APO 3	2.2	0.00	5.345	0.170	0.51	0.05	
APO 3	3.4	0.00	7.718	0.073			
FAA 1B	0.7	0.00	0.703	0.115	1.74	1.1	
FAA 1B	1.5	0.00	1.163	0.175	0.42	0.06	
FAA 1B	2.5	0.00	3.530	0.180	0.53	0.08	
FAA 1B	3.5	0.00	5.428	0.112			
FAA 6	1.02	0.00	1.750	0.150	0.19	0.01	
FAA 6	1.85	0.00	6.123	0.098			
POV 2	1.1	0.00	1.555	0.140	0.26	0.03	
POV 2	1.55	0.00	3.290	0.085	0.24	0.02	
POV 2	2.3	0.00	6.423	0.155	0.65	0.09	

(Continues)

TABLE 1 (Continued)

Sample	Core depth in m	Error ±	Age kyr cal BP	Error ±	Accr.-rate/ sed-rate m/kyr	Linear error propagation ±	Massive branched facies
POV 2	3.4	0.00	8.125	0.080			
TAI 1	1.2	0.00	0.650	0.040	0.81	0.06	
TAI 1	2.77	0.00	2.595	0.115			
All reefs:					m/kyr		
Reef accr.	Mean Belize				2.91		
	Mean Maldives				7.25		
	Mean Bora Bora				5.84		
$N = 79$	Total mean				5.05		
	SD				4.14		
Lagoon sed.	Mean Belize				1.44		
	Mean Maldives				0.68		
	Mean Bora Bora				0.54		
$N = 72$	Total mean				0.89		
	SD				0.85		
Branched coral reefs:							
Reef accr.	Total				5.18		
SD	Total				4.47		
	Mean Belize				2.64		
	Mean Maldives				7.80		
	Mean Bora Bora				5.57		
Palaeo waterdepth (mean in m)				3.06			
Massive coral reefs							
Reef accr.	Total				5.07		
SD	Total				3.28		
	Mean Belize				3.24		
	Mean Maldives				4.53		
	Mean Bora Bora				6.75		
Palaeo waterdepth (mean in m)				7.46			

Note. Age data from reef cores include calibrated C14 ages (Belize, Maldives) and U-series ages (French Polynesia). Age data from lagoon cores are all calibrated C14-ages. B: branched coral facies; M: massive coral facies. Averages at bottom of table. SD: standard deviation.

accretion and lagoon sedimentation rates, the linear error propagation (ep) was calculated using the formula:

$$\text{ep} = \left(dd/t_{12}\right) + \left(\left(d \times dt_{12}\right) / (t_{12})^2\right) \tag{3}$$

where d is the difference in core depths (D) in metres; dd is the error in difference in core depth; t_{12} is the difference in age dates in kyr; and dt_{12} is the error in difference in age dates.

When the linear error propagation, which is a conservative measure of variability, exceeded calculated accretion and sedimentation rates, values were excluded from further analysis. This was the case when sampling points were close together, typically less than 1 or 2 m apart. In order to compare reef accretion rates with the influence of sea-level, rates of sea-level rise were calculated for intervals of 500 years based on local Holocene sea-level reconstructions for these three regions (Figure 5). In situ corals were identified using taphonomic screening for corallites oriented upcore, together with the presence/absence of marine encrustation and bioerosion (Blanchon & Perry, 2004). Palaeoecologic reconstructions were then used to estimate palaeobathymetry (Abbey et al., 2011). The vertical distance from each datum to the respective local sea-level curve was taken as palaeo-water depth (Figure 5). The regional sea-level curves exhibit steep slopes during the early-to-mid Holocene and gentle slopes during the late Holocene. Although the Belize and Maldives curves are characterized by sea-level rise, the Bora Bora curve exhibits a rise and a fall that is after an early-to-mid Holocene rise, late

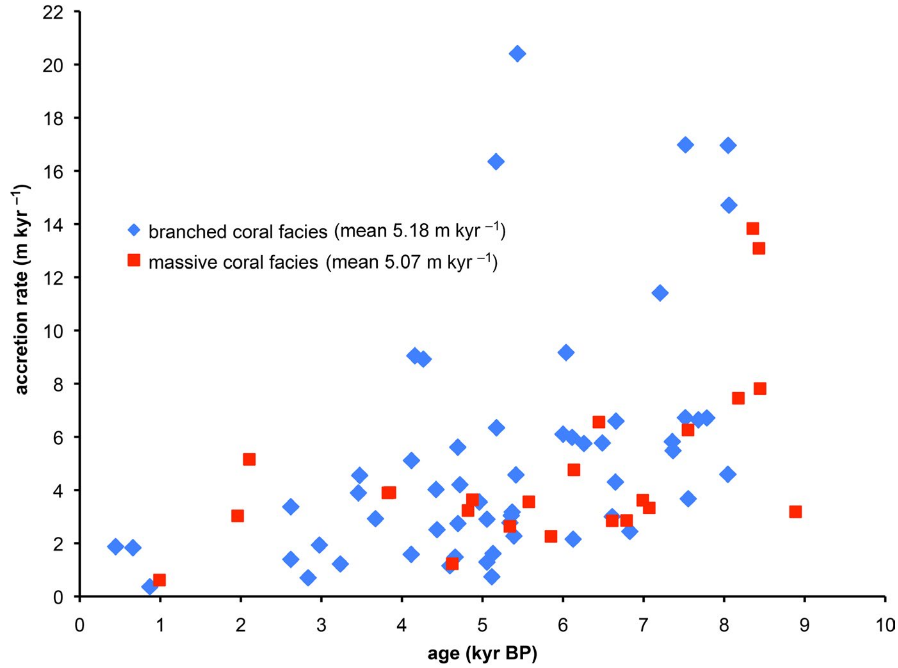

FIGURE 8 Accretion rates of branched and massive coral reef facies versus age

Holocene sea-level exceeds modern level and then falls to the present level. The Holocene sea surface temperature (SST) data set of Marcott, Shakun, Clark, and Mix (2013), which is based on 73 globally distributed Holocene climate records, was used as a climate proxy. Subsidence rates originate from calculations that are based on core depths, palaeobathymetry reconstructions and U-series dates from corals selected from underlying Pleistocene sections in cores (Gischler, Lomando, Hudson, & Holmes, 2000; Gischler et al., 2008, 2016).

The composition of 40 petrographic thin sections along three cores of Glovers Reef (Belize), one core from Rasdhoo Atoll (Maldives) and four cores from Bora Bora (French Polynesia) have been quantified using a point counter, counting 300 items per section (van der Plas & Tobi, 1965). Five categories were counted including reef framework (largely coral and coralline algae), porosity, aragonite cement, high-Mg calcite cement and fine-grained internal sediment. The Glovers Reef core holes were used to install 3 m deep wells for water sampling. Ordinary PVC pipes, slotted over the lower 0.5 m, were inserted into the core holes with the open space outside of the pipes being filled along the main part with reef sand and at the top with hydraulic cement. Water samples were taken four times in each well and from surface waters during 16 to 20 August 1996 and 4 to 8 April 1997. Samples were analysed for oxygen concentration and alkalinity by titration in the field using a Hach portable water analysis kit. Two dye experiments were performed by injecting a rhodamine solution (1 g dissolved in 10 l ocean water) in to each well and subsequently sampling the well water over time periods of up to 100 hr during August 1996 and April 1997. Water samples were pumped out of the wells and dyed water into the wells using a small peristaltic pump. Dye concentrations were measured in 36 water samples at the hydrogeology laboratory, University of Tübingen, Germany, using a spectrofluorometer in September 1996 and May 1997. The $\delta^{18}O$ of water and the $\delta^{13}C$ of dissolved inorganic carbon (DIC) were measured using a ThermoFinnigan DeltaPlus mass spectrometer at the stable isotope laboratory, University of Miami, USA, in June 1997, and reported relative to standard mean ocean water (SMOW). Analytical precision was 0.2‰ for $\delta^{18}O$ and $\delta^{13}C$.

Statistical analyses during this work were made using the software PAST (Hammer, Harper, & Ryan, 2001).

3 | RESULTS

Vertical reef accretion rates range from below 1 m/kyr in the late Holocene to more than 20 m/kyr in the early Holocene (Figures 6 and 7; Table 1). There is a statistically significant, overall trend of decreasing accretion rates throughout the Holocene. The total mean vertical reef accretion rate amounts to 5.05 m/kyr. The standard deviation (*SD*) equals 4.14. The Indo-Pacific accretion rates are significantly higher than the Atlantic rates that is the mean values for Rasdhoo Atoll (7.25 m/kyr) and Bora Bora (5.84 m/kyr) clearly exceed the Belize mean value (2.91 m/kyr). Accretion rates in core sections with predominantly branched corals (mean 5.18 m/kyr; *SD* 4.47) are statistically similar to those in reef sections dominated by massive corals (mean 5.07 m/kyr; *SD* 3.28) (Figure 8; Table 1). The average palaeodepth amounts to 3.06 m in the branched coral reef facies and to 7.46 m with massive coral reef facies (Tables 1, 2). Correlations between accretion rate and potential controlling factors such as rate of

TABLE 2 Data on reef accretion rates, palaeo-waterdepth, rate of sea-level rise and SST anomaly used for analyses

Age (kyr)	Accr.-rate (m/kyr)	SST anomaly (°C)
Belize		
10.00	5.94	0.27
9.00	5.35	0.4
8.00	4.76	0.38
7.00	4.17	0.46
6.00	3.58	0.33
5.00	2.99	0.37
4.00	2.43	0.2
3.00	1.82	0.05
2.00	1.26	−0.04
1.00	0.64	−0.05

Age (kyr)	Accr.-rate (m/kyr)	Palaeodepth (m)	Rate of SL-rise (m/kyr)
Belize			
4.875	3.63	0.69	0.55
6.445	6.56	5.06	1.2
5.055	1.29	0.25	0.55
6.65	4.3	0.38	1.53
3.235	1.22	1.25	0.33
6.61	3.0	3.13	1.53
0.99	0.61	3.44	0.33
6.135	4.76	4.25	1.2
4.435	2.51	2.00	0.5
6.259	5.75	5.31	1.2
4.695	2.74	1.75	0.55
5.85	2.26	4.13	0.72
2.975	1.93	1.50	0.33
6.00	6.1	5.63	1.2
6.99	3.61	10.19	1.53
0.66	1.83	2.25	0.33
5.34	2.63	9.00	0.55
7.07	3.33	11.50	2.61
5.39	2.27	0.19	0.55
5.34	2.77	0.19	0.55
2.835	0.7	0.00	0.33
5.055	2.9	0.63	0.55
5.575	3.56	2.63	0.72
6.61	2.84	5.06	1.53
3.825	3.89	0.75	0.5
4.625	1.23	3.50	0.55
0.87	0.36	0.75	0.33

(Continues)

TABLE 2 (Continued)

Age	Accr.-rate	SST anomaly
Maldives		
10.00	15.55	0.27
9.00	13.70	0.4
8.00	12.05	0.38
7.00	10.21	0.46
6.00	8.49	0.33
5.00	6.71	0.37
4.00	4.93	0.2
3.00	3.29	0.05
2.00	1.52	−0.04
1.00	0.00	−0.05

Age	Accr.-rate	Palaeodepth	Rate of SL-rise
Maldives			
3.475	4.55	0	0.35
4.115	1.58	2.29	0.38
7.68	6.64	3.14	8.0
4.595	1.15	0	0.38
7.205	11.41	0	3.24
8.06	14.71	1.52	14.0
6.125	2.15	0	1.14
7.52	16.98	0	8.0
8.05	16.96	4.1	14.0
0.445	1.87	0.48	0.3
2.105	5.15	3.0	0.3
3.85	3.9	11.33	0.35

Age	Accr.-rate	SST anomaly
Bora Bora		
10.00	8.43	0.27
9.00	7.78	0.4
8.00	7.22	0.38
7.00	6.67	0.46
6.00	6.11	0.33
5.00	5.37	0.37
4.00	4.81	0.2
3.00	4.07	0.05
2.00	3.33	−0.04
1.00	2.78	−0.05

Age	Accr.-rate	Palaeodepth	Rate of SL-rise
Bora Bora			
4.960	3.55	0.92	0.68
6.038	9.17	3.68	1.42
6.656	6.59	8.29	2.53

(Continues)

TABLE 2 (Continued)

Age	Accr.-rate	Palaeodepth	Rate of SL-rise
7.518	6.72	12.11	3.95
8.176	7.45	13.42	5.26
8.887	3.18	13.16	9.1
2.620	1.39	0.53	0
4.265	8.92	2.63	0.53
4.719	4.2	6.32	0.68
5.415	4.57	8.68	0.92
6.488	5.77	12.11	1.42
7.551	6.26	15.79	3.95
8.446	7.82	16.84	5.26
4.160	9.05	2.5	0.53
4.423	4.02	4.61	0.53
5.174	6.34	7.11	0.92
6.112	5.98	11.97	1.42
6.789	2.85	14.74	2.53
8.432	13.09	15.39	5.26
5.130	1.61	0.53	0.92
7.365	5.48	0.26	2.63
7.785	6.71	1.18	3.95
8.356	13.84	2.37	5.26
1.960	3.03	3.16	0
4.820	3.23	2.24	0.68
5.116	0.74	1.9	0.92
7.356	5.82	0.13	2.63
4.661	1.48	2.82	0.53
7.554	3.67	2.76	3.95
6.829	2.44	6.46	2.53
8.046	4.59	2.52	5.26
2.620	3.37	2.2	0.53
4.118	5.11	6.99	0.53
3.459	3.89	2.69	0.53
5.434	20.41	9.05	0.53
3.671	2.92	0.09	0.53
5.357	3.04	6.13	0.92
4.693	5.61	2.43	0.68
5.168	16.35	1.13	0.92
5.368	3.17	4.14	0.92

SST: sea surface temperature.

sea-level rise, SST and palaeodepth exhibit different strengths. In the Belize ($r = 0.547$, $p < 0.003$) and the Maldives examples ($r = 0.861$, $p < 0.0003$), there are statistically significant positive correlations between accretion rate and rate of sea-level rise (Table 3). In all data, this correlation is also significant ($r = 0.569$, $p < 0.000$). In Belize ($r = 0.812$, $p < 0.004$), the Maldives ($r = 0.808$, $p < 0.005$), Bora Bora ($r = 0.830$, $p < 0.003$) and in all data ($r = 0.626$, $p < 0.0002$), accretion rates show statistically significant correlations with the SST anomaly (Figures 6 and 7). There are no significant correlations between reef accretion rate and palaeodepth (Table 3).

TABLE 3 Correlation matrices including age, accretion rate, palaeo-waterdepth and rate of sea-level rise for the three study areas and all locations

	Age	Accr.-rate	Palaeodepth	Rate SL-rise
(a) Belize				
Age		0.0001	0.015	0.000
Accr. rate	<u>0.670</u>		0.071	0.003
Palaeodepth	<u>0.464</u>	<u>0.353</u>		0.0001
Rate SL rise	<u>0.742</u>	<u>0.547</u>	<u>0.677</u>	
(b) Maldives				
Age		0.007	0.804	0.0026
Accr. rate	<u>0.731</u>		0.880	0.0003
Palaeodepth	−0.080	−0.049		0.987
Rate SL rise	<u>0.784</u>	<u>0.861</u>	0.005	
(c) Bora Bora				
Age		0.089	0.000	0.000
Accr. rate	0.272		0.227	0.324
Palaeodepth	<u>0.512</u>	0.195		0.001
Rate SL rise	<u>0.879</u>	0.160	<u>0.498</u>	
(d) All locations				
Age		0.000	0.0001	0.000
Accr. rate	<u>0.468</u>		0.126	0.000
Palaeodepth	0.422	0.173		0.045
Rate SL rise	<u>0.665</u>	<u>0.569</u>	0.227	

Note. *r*-values are shown in lower left corners; *p*-values in upper right corners of matrices. Statistically significant correlation at $p < 0.05$ (underlined).

Background sedimentation rates in adjacent reef lagoons are much lower when compared to vertical reef accretion rates (Figures 6 and 9). Most values are below 1 m/kyr. The highest numbers reach 5 m/kyr that is in the late Holocene Belize examples. There is a statistically significant trend towards higher sedimentation rates during the Holocene. The overall mean lagoonal sedimentation rate is 0.89 m/kyr (*SD* 0.85), with the lowest means found at Bora Bora (0.54 m/kyr), moderate means found at Rasdhoo Atoll (0.68 m/kyr) and the highest means occurring in the Belize atoll lagoons (1.44 m/kyr). The contact of the basal lagoonal carbonate and the underlying mangrove peat is characterized in 14 examples by hiatuses ranging from 1.70 to 5.38 kyr with a mean of 3.05 kyr (Table 4).

Recovery in reefal rotary cores ranged from 0% to 100% with a mean of 27.3% or 0.41 m per barrel (Figure 10; Table S2). There is a trend to lower recovery, or, in other words, an increase in the unconsolidated sand and rubble facies downcore. This trend is statistically significant in that a negative

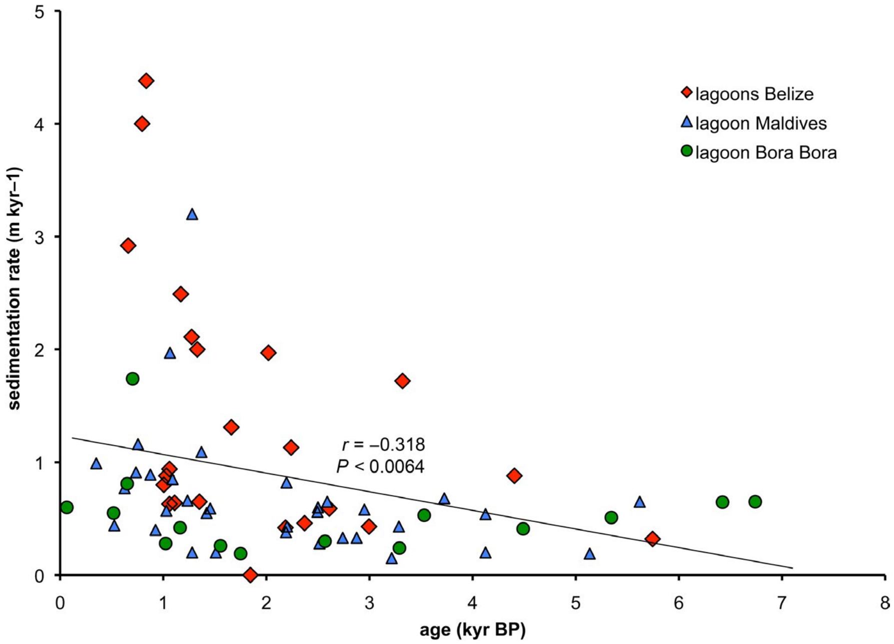

FIGURE 9 Lagoon sedimentation rates versus age

TABLE 4 Between the basal peat and overlying carbonate in cores there usually is a considerable hiatus. Note that in two cases, corals superposing peat have been dated

Core	Peat age (year)	±	Basal carb. age (year)	±	Hiatus (year)	Source
Belize						
G 5	8,765	235	6,225	115	2,540	1, 2
G 7	8,470	140	4,685	165	3,795	1, 2
T 4	6,395	105	3,445	115	2,950	1, 2
T 7	6,840	180	4,380	150	2,460	1, 2
L 5	7,800	140	3,850	200	3,950	1, 2
L 6	7,545	125	2,170	130	5,375	1, 2
LR 10[a]	6,850	135	4,813	33	2,037	3, 4
LR 14[a]	7,295	90	5,105	125	2,190	3, 4
Maldives						
16	10,320	100	7,850	140	2,470	5
Bora Bora						
POV 2	8,125	80	6,423	155	1,702	6
APO 3	7,717	72	5,345	170	2,372	6
FAA 1B	5,427	112	3,530	180	1,897	6
CHA 1C	10,654	46	6,100	100	4,545	6
FAA 6	6,123	98	1,750	150	4,373	6
				Mean	3,047	
[a]Coral on peat				Min.	1,702	
				Max.	5,375	
1	Gischler (2003)					
2	Schultz et al. (2010)					
3	Gischler and Lomando (2000)					
4	New data					
5	Klostermann and Gischler (2015)					
6	Isaack et al. (2016)					

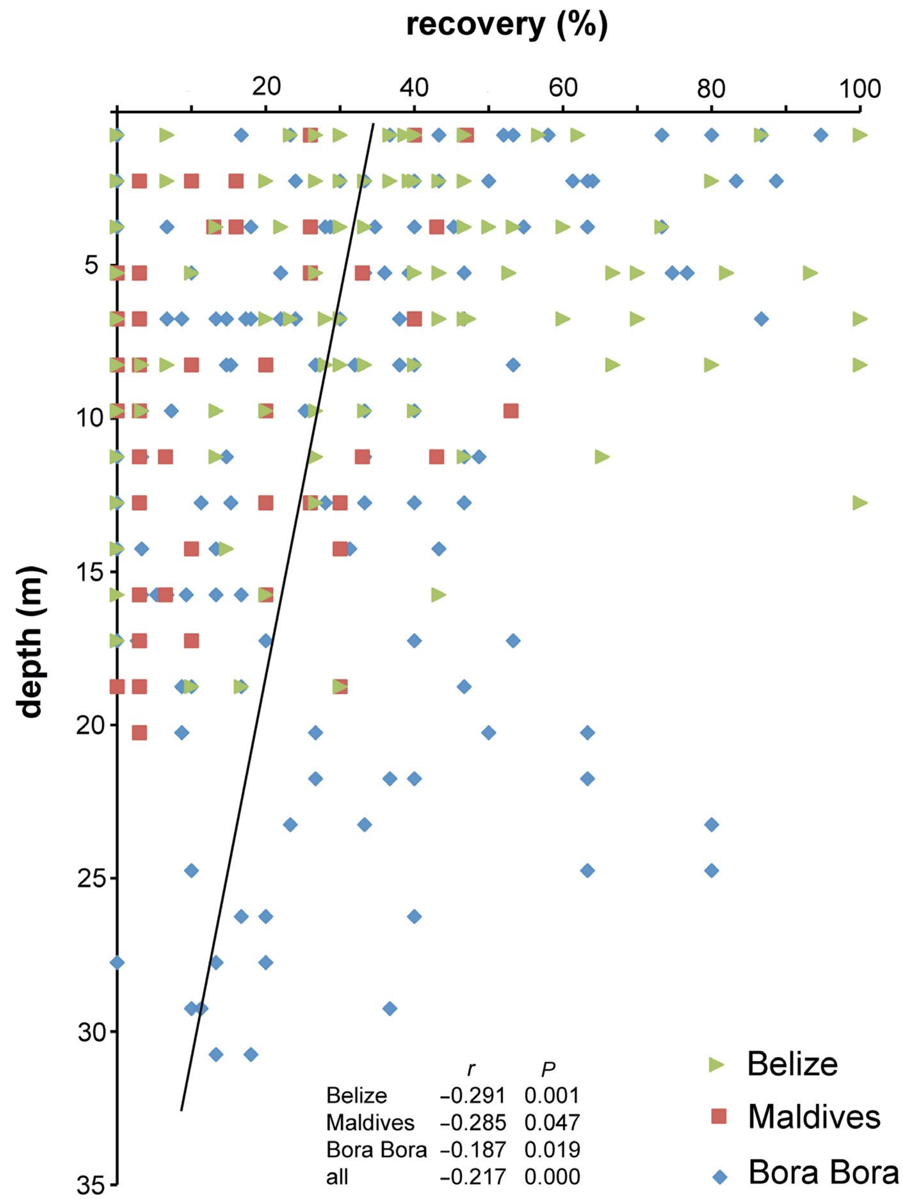

FIGURE 10 Core recovery data show a statistically significant decreasing trend downcore. Recovery is interpreted as a proxy of reef consolidation that is the degree of marine cementation

correlation between recovery and depth exists ($r = -0.217$, $p < 0.000$). A comparable downcore trend does not exist in the absolute amounts of cements in cores (Table 5). Acicular aragonite and microcrystalline high-Mg calcite cements are most common, and make up 2.4% to 27.5% of the rock volume (average 8.6%; $SD = 4.6\%$). Volumes of internal sediment amount to 25.4%, that of framework builders to 51% and porosity to 14.8% on average (Table 5). There is also a trend towards increasing amounts of the unconsolidated sand and rubble facies from windward towards leeward locations visible in the Glovers Reef, Lighthouse Reef and the Bora Bora fringing reef cores (Figure 11). Likewise, marine cements are more abundant on windward, compared to leeward and lagoonal core positions (Table 5). Reef well water samples from Glovers Reef exhibit lower oxygen and higher alkalinity values in leeward versus windward positions (Table 6). There are no significant or meaningful differences in oxygen concentration and alkalinity in surface water samples. The same is true for $\delta^{18}O$ and $\delta^{13}C$ values of surface waters, which do not show significant differences and range from 0 to +1‰ SMOW (Table 6). The $\delta^{18}O$ values of well waters are between 0 to + 1‰ SMOW. The $\delta^{13}C$ values of well water ranges from −2.1 to +0.83‰ SMOW, with the heaviest values measured in the windward well and the lightest values in the leeward well. Rhodamine experiments in the Glovers Reef wells showed that dye concentrations decreased most quickly in the windward well and most slowly in the leeward well (Figure 12).

4 | DISCUSSION

4.1 | Reef accretion

The rates of Holocene vertical reef accretion in Belize, the Maldives and Bora Bora are in the range of existing

TABLE 5 Results of point-counting in 40 petrographic thin sections from 11 rotary cores

Sample	Core depth (m)	Porosity (%)	Framework (%)	Aragonite cement (%)	HMC cement (%)	Internal sediment (%)	Cement total (%)
Glovers							
GR 1-windward							
7	0.75	21.70	18.90	0.70	10.00	48.70	10.70
6	2.25	25.70	48.30	5.30	10.70	10.00	16.00
5	5.25	22.30	62.70	4.70	3.30	7.00	8.00
4	6.75	34.70	48.70	4.70	1.00	11.00	5.70
Mean		26.10	44.65	3.85	6.25	19.18	10.10
GR 2-lagoon							
12	5.25	22.70	57.70	5.00	2.00	12.70	7.00
11	7.50	26.70	57.30	4.30	2.70	9.00	7.00
10	11.25	29.70	58.30	7.70	1.00	3.30	8.70
GR 3-leeward							
13	0.75	22.70	39.30	0.70	2.30	35.00	3.00
Mean		25.45	53.15	4.43	2.00	15.00	6.43
Lighthouse							
LR 7-windward							
1	1.00	11.70	56.30	2.30	11.30	18.30	13.60
1.5	1.50	13.00	45.00	4.30	7.70	30.00	12.00
5.25	5.25	14.70	64.00	3.70	6.70	11.00	10.40
5.75	5.75	8.30	41.00	0.70	9.30	40.70	10.00
Mean		11.93	51.58	2.75	8.75	25.00	11.50
LR 11-lagoon							
11-2	2.00	10.70	40.00	1.30	3.00	45.00	4.30
LR 10-leeward							
10-4	4.00	19.00	5.30	0.00	8.30	67.30	8.30
Mean		14.85	22.65	0.65	5.65	56.15	6.30
Rasdhoo							
Core 1-windward							
1-1.5	1.50	11.60	71.90	1.60	2.00	12.90	3.60
1-6	6.00	17.00	72.00	1.70	5.70	3.70	7.40
1-10.5	10.50	10.30	61.00	2.00	1.30	25.30	3.30
1-10.7	10.70	8.60	59.20	0.80	1.60	29.80	2.40
1-11	11.00	6.50	26.90	4.30	9.70	52.70	14.00
Mean		10.80	58.20	2.08	4.06	24.88	6.14
Bora Bora							
Puhia 1-windward							
1-1.5	1.50	10.00	63.30	0.30	6.70	19.70	7.00
1-2.25	2.25	7.70	73.30	2.30	10.30	6.30	12.60
Puhia 2-windward							
2-1.5	1.50	6.90	69.90	6.90	5.20	11.00	12.10
2-3	3.00	8.00	51.20	5.70	21.80	12.60	27.50
2-4.5	4.50	21.40	52.10	1.90	5.80	18.70	7.70
2.6	6.00	14.60	54.40	5.00	2.50	23.50	7.50

(Continues)

TABLE 5 (Continued)

Sample	Core depth (m)	Porosity (%)	Framework (%)	Aragonite cement (%)	HMC cement (%)	Internal sediment (%)	Cement total (%)
Puhia 3-windward							
3-7.5	7.50	16.00	58.30	2.50	3.70	19.60	6.20
3-10.5	10.50	15.40	50.70	6.00	5.50	22.40	11.50
3-11.25	11.25	13.00	56.30	2.30	3.30	25.00	5.60
3-13.5	13.50	1.70	50.60	2.20	9.60	36.00	11.80
Mean		11.47	58.01	3.51	7.44	19.48	10.95
FAA 1-leeward							
1-1	0.50	17.00	50.00	3.70	7.30	22.00	11.00
1-2	1.00	12.70	44.70	3.70	6.00	33.00	9.70
2-1	2.25	6.90	76.40	3.40	3.40	9.90	6.80
3-1	3.75	11.00	65.30	3.30	3.30	17.00	6.60
4-1	5.00	14.30	59.70	2.30	1.70	22.00	4.00
4-2	5.50	11.30	59.30	4.70	2.00	22.70	6.70
5-1	6.75	7.70	42.30	2.70	7.70	39.70	10.40
6-1	8.00	12.00	30.70	2.70	2.00	52.70	4.70
6-2	8.50	23.60	19.20	4.00	4.40	48.80	8.40
6-3	9.00	11.80	29.50	1.80	7.30	49.50	9.10
7-1	9.75	12.90	47.50	3.90	6.30	29.40	10.20
Mean		12.84	47.69	3.29	4.67	31.52	7.96
Total mean		14.84	50.96	3.18	5.64	25.37	8.60

Note. Framework corresponds largely to corals and coralline algae. Aragonite cement includes the acicular (needle) and botryoidal types. High-Mg-calcite (HMC) cement includes peloidal and bladed types. Internal sediment is probably cemented by microcrystalline high-Mg calcite cement, which has not been quantified.

compilations. Dullo (2005) reported average accretion rates of 4.4 m/kyr for the Indo-Pacific and 6.1 m/kyr for the Caribbean realms. Montaggioni (2005) noted highly variable vertical accretion rates in the Indo-Pacific region ranging from 1 to 30 m/kyr (mode 6 to 7 m/kyr) in framework-dominated reefs. High variability in accretion rate may be seen even in reefs of the same local area such as in the Capricorn Bunker Group of the southern Great Barrier Reef (Dechnik, Webster, Davies, Braga, & Reimer, 2015). Hubbard (2009) reported average vertical accretion rates of 3.1 to 3.8 m/kyr for the Caribbean region and Toth, Kuffner, Stathakopoulos, and Shinn (2018) ca 3 m/kyr for the Florida Reef Tract that is lower than the Caribbean rates of Dullo (2005). In all of these studies, however, quantitative correlations with environmental controlling factors are largely lacking.

The decreasing trend in reef accretion rate in Belize, the Maldives and Bora Bora during the Holocene is most probably related to the decrease in the rate of sea-level rise, that is the reduction in accommodation space, and to climate variation as expressed in the SST anomaly (Marcott et al., 2013). The rate of sea-level rise (Figure 5; Table 2) and, hence, the creation of accommodation space is crucial for vertical reef growth and accretion, and therefore shows statistically significant correlations with reef accretion rate. Lateral accretion (reef progradation), as observed in Bora Bora (Gischler et al., 2016), has not been taken into account here. Rates of sea-level rise in 500 year time bins are as high as 14 m/kyr and average 1.96 m/kyr (Table 2). Somewhat warmer and wetter conditions during the early to mid Holocene Climate Optimum apparently also supported increased reef accretion during this time window as seen in the positive correlations of accretion rates with the Holocene SST climate anomaly (Marcott et al., 2013). This climate anomaly exhibits a high fluctuating around 0.4°C from ca 10 to 5 kyr BP, a subsequent decreasing trend towards −0.4°C, and a strong modern increase to 0.6°C (Figure 6). The data set comprises only a few archives from the Pacific; however, Stott et al. (2004) have shown that SSTs in the western tropical Pacific have decreased over the past 10 kyr, as in the compilation of Marcott et al. (2013). Recently, Toth et al. (2018) concluded also that the Holocene decline in reef accretion in the Florida Reef Tract was largely controlled by a cooling climate.

It has been observed earlier that reefs with a massive coral framework accrete as fast as reefs dominated by branched corals, both in the Caribbean (Gischler, 2008; Hubbard, 2009) and the southern Great Barrier Reef (Dechnik et al.,

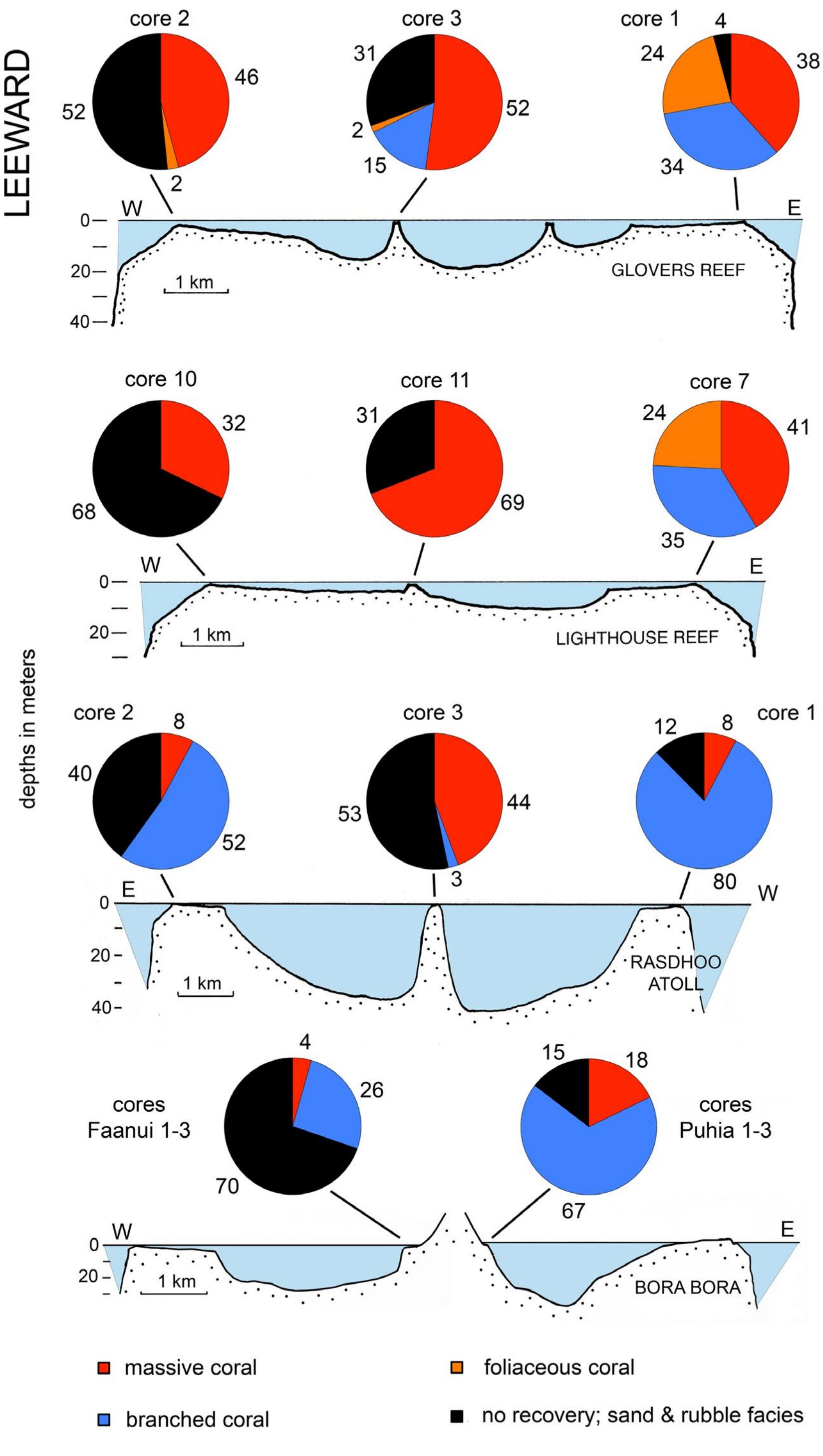

FIGURE 11 Schematical cross-sections through Glovers Reef, Lighthouse Reef, Rasdhoo Atoll and Bora Bora showing core composition. Numbers on pie diagrams are in percent. Missing core recovery corresponds to unconsolidated sand and rubble facies. Sections are oriented so that the windward reef side is on the right hand side of the figure. Note that cores were considered only when they comprised complete or close to complete Holocene sections

2015). Different growth strategies and bathymetrical variation in bioerosion have been used to explain this phenomenon (Gischler, 2008; Hubbard, 2009). Massive corals grow relatively slowly but continuously in somewhat deeper water, whereas branched corals grow relatively quickly in shallower water but are repeatedly broken down by storms. At the same time, rates of bioerosion decrease with increasing water depth (Kiene & Hutchings, 1994; Vogel, Gektidis, Golubic, Kiene, & Radtke, 2000). These findings, and the fact that the reefs studied here largely kept up with sea-level, underline that there is not necessarily a correlation between reef architecture, that is coral composition (massive vs. branched) and response to sea-level rise in the Holocene as assumed earlier (Davies & Marshall, 1980; Neumann & Macintyre, 1985). More studies from other regions are needed, which compare massive and branched coral reefs statistically, in order to further validate these new findings.

The increase in accommodation space for reef growth via relative sea-level rise may also be caused by subsidence. Existing late Quaternary subsidence data for the three study areas range from 0.04 to 0.11 m/kyr in Belize (Gischler et al., 2000), 0.09 to 0.16 m/kyr in the Maldives (Gischler et al.,

TABLE 6 Oxygen and carbon stable isotopes as well as alkalinity and oxygen concentrations of surface and well water from Glovers Reef, Belize

Sample	$\delta^{18}O$ ‰ SMOW	$\delta^{13}C$ ‰ SMOW	Alkalinity (mg/l)	O_2 (mg/l)
Surface water				
Core 1 (windward)	0.81	0.44	103.8	7.30
Core 1	0.08	0.57	110.8	7.31
Core 1			101.0	7.25
Core 1			109.5	7.35
Mean	0.45	0.51	106.28	7.30
Core 2 (leeward)	0.40	0.34	102.7	6.66
Core 2	0.24	0.98	107.8	6.70
Core 2			102.7	6.80
Core 2			102.5	6.90
Mean	0.32	0.66	103.93	6.77
Core 3 (lagoon)	0.37	0.40	110.0	6.23
Core 3	0.41	0.49	113.3	6.55
Core 3			116.0	6.53
Core 3			119.2	6.85
Mean	0.39	0.45	114.63	6.54
Well water				
Core 1 (windward)	0.71	0.80	101.1	2.12
Core 1	1.01	0.83	108.0	2.73
Core 1	0.85	0.41	105.3	2.20
Core 1	1.00	0.48	116.2	2.70
Mean	0.89	0.63	107.65	2.44
Core 2 (leeward)	0.65	−1.75	130.2	0.00
Core 2	0.70	−1.80	160.0	0.00
Core 2	1.02	−1.81	120.0	0.00
Core 2	0.85	−2.10	134.2	0.00
Mean	0.81	−1.87	136.10	0.00
Core 3 (lagoon)	0.25	−0.19	148.8	1.13
Core 3	0.80	−0.31	150.5	1.38
Core 3	1.01	−0.15	143.0	1.05
Core 3	1.00	−0.44	141.7	1.11
Mean	0.77	−0.27	146.00	1.17

Note. SMOW: standard mean ocean water.

2008) and 0.05 to 0.14 m/kyr for Bora Bora (Gischler et al., 2016). This translates into a range of absolute subsidence values of 0.4 to 1.6 m during the past 10 kyr. Because these numbers are one to two orders of magnitude lower than accommodation space provided by glacio-eustasy, subsidence is regarded as much less significant for reef accretion when compared to the effects of sea-level rise.

Only the Indo-Pacific rates of vertical reef accretion from the Maldives and French Polynesia, at least in part, exceed the rates of sea-level rise of the 21st century predicted by the IPCC (2013) or by other scenarios that are on the same order of magnitude (DeConto & Pollard, 2016; Woodruff et al., 2013). It remains to be seen whether even the Indo-Pacific examples will be able to keep up with rising sea-level in the light of the fact that SSTs, the occurrences of bleaching events and disease, and ocean acidification will increase probably (Eyre et al., 2018; Hughes et al., 2017; Pandolfi et al., 2011). Recently, Perry et al. (2018) stated that few reefs in both the Caribbean, including Belize, and the Indian Ocean, including the Maldives, would be able to match projected 21st century rates of sea-level rise based on estimates of vertical growth potential.

4.2 | Lagoon sedimentation

The increase in lagoonal background sedimentation rates during the Holocene may be related to progressive deepening that is a slight but continuous increase in accommodation space over time. This assumption is supported by the existence of fining-upward trends observed in the lagoonal successions (Gischler, 2003; Isaack et al., 2016; Klostermann & Gischler, 2015). The quantitative comparison of lower background sedimentation rates (0.89 m/kyr on average) as compared to the significantly higher reef accretion rates (5.05 m/kyr on average) explains why many modern reefs and carbonate platforms are unfilled buckets that is have saucer-shaped cross-sections (Purdy & Gischler, 2005; Schlager, 1981). Only the accommodation space in small reefs and platforms occupying a few hundred square kilometres or less has been filled during the Holocene, largely by lateral sediment transport via sand aprons (Purdy & Gischler, 2005; and references therein). Over longer time scales during the Pleistocene, the saucer-shape of reefs and carbonate platforms is usually exacerbated by preferential karst dissolution in platform interiors during glacial sea-level lowstands as demonstrated by Purdy (1974) and Purdy and Winterer (2001) both in experiments and by the existence of Pleistocene reef island examples with central topographic depressions. Schlager and Purkis (2013) have shown that the bucket shape of carbonate platforms may also be a consequence of biotic self organization, based on the fact that carbonate producers at the margin potentially have easier access to food and nutrients and are less prone to be buried in sediment.

The considerable hiatus between mangrove peat and basal carbonates observed in a number of cores has also been described from other reefal successions and has been modelled (Kim, Fouke, Quinn, Kerans, & Taylor, 2012; Tipper, 1997, and references therein). A reasonable explanation is the

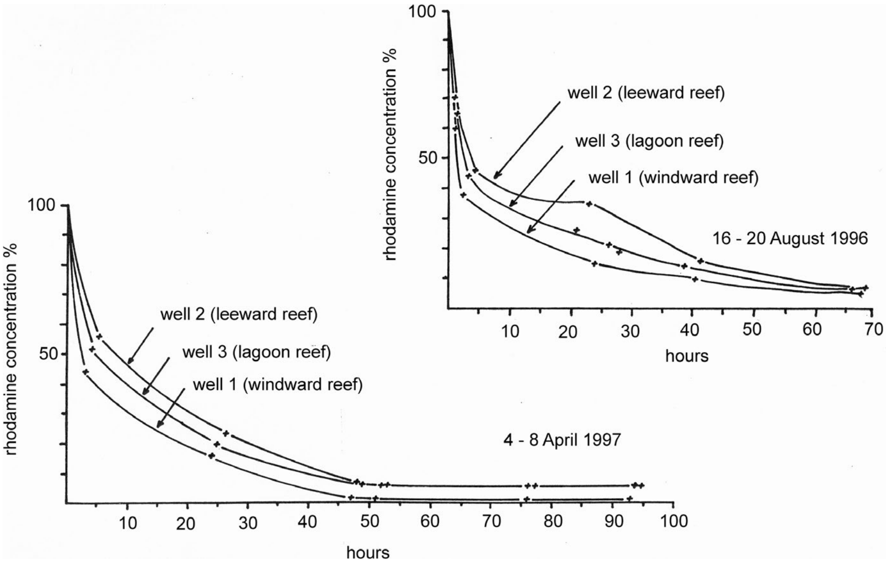

FIGURE 12 Results of rhodamine dye experiments (decreasing concentrations with time) in three Glovers Reef wells

inimical bank water model, which underlines the deleterious effect of turbid and nutrient-rich waters created after the initial flooding of subaerially exposed reef banks with soil cover (Lighty, Macintyre, & Stuckenrath, 1978; Schlager, 1981). These two factors in combination with unsuitable substrate, strong hydrodynamics, and relief of antecedent substrate are potentially responsible for the fact that carbonate-producing organisms need a certain amount of time to become established on inundated platforms and start what is called the carbonate factory. The age data from this study shows that the lag time may extend for several thousand years. Recent observations by Hubbard, Gill, and Burke (2013) on Lang Bank, St. Croix, have challenged the inimical bank water hypothesis because it was shown that Holocene reefs had drowned only well after platform inundation for as yet unknown reasons.

4.3 | Reef consolidation

Recovery during rotary drilling is largely a function of reef consolidation that is the degree of early marine cementation. A downcore decrease in recovery was common in the reef cores analysed here. Comparable observations have been made by James, Ginsburg, Marszalek, and Choquette (1976) who noticed that the most extensive cementation occurred in the upper portions (0.5 to 1 m) of excavated Belize barrier and atoll reef margin pavements. The most probable explanation for this observation is the time available for marine cementation (Tucker & Wright, 1990, pp. 325–327, and references therein). During the relatively rapid early to mid Holocene sea-level rise, much less time was available for submarine cementation in the reef framework as compared to the mid to late Holocene time window when sea-level rise had decelerated significantly. This interpretation may be somewhat biased by the existence of reef cavities, which would also reduce core recovery during drilling. It is not entirely clear why the downcore trend in core recovery is not matched by a similar decrease in cement abundance (Table 5). Possible explanations might be the patchiness of cement distribution and the relatively low amounts of cementation (<10% on average) in general. Another problem is the difficulty of identifying microcrystalline cement (Friedman, 1985; Reid, Macintyre, & James, 1990; Scoffin, 1993) and its quantification in the internal sediment portions, which make up 25.4% of the reef on average (Table 5). The windward-to-leeward decrease in core recovery that is the increase in the unconsolidated sand and rubble facies, underlines the importance of flushing reef interstices with marine waters saturated with regard to calcium carbonate during cementation. This trend is also seen in the distribution of marine cements in that average abundances are higher at windward rather than leeward core positions (Table 5). The dye experiments and the measured gradient in oxygen concentration in well waters in Belize have shown that flushing with marine waters is indeed stronger on the windward side. The lower alkalinities measured in the windward well compared to the leeward and lagoon locations suggest that cementation preferentially occurs at a higher rate at the former position, presumably reducing alkalinity in pore waters. The negative $\delta^{13}C$ values measured in the lagoon and leeward well water may indicate the influence of heterotrophic bacteria, which introduce light, ^{12}C-enriched carbon into the DIC pool. Pigott and Land (1986) have shown that microbial sulphate reduction may trigger calcium carbonate precipitation in reef cavities. In general, stronger cementation at windward rather than leeward reef positions has been reported from various other Holocene reef sites, for example from the southern and central Great Barrier Reef (Marshall, 1985; Marshall & Davies, 1981) and from Mururoa Atoll (Aissaoui & Purser, 1985). In order to further validate these interpretations, a challenging task will be the conduction of further studies quantifying the comparatively low volumes of cements in Holocene reef core material.

5 | CONCLUSIONS

Holocene tropical reef accretion and adjacent lagoonal sedimentation rates from Belize, the Maldives and French Polynesia have been quantified, statistically analysed, and compared with climate proxy data. Vertical reef accretion rates, which average 5.05 m/kyr, have been decreasing during the Holocene, probably due to both decreases in the rate of sea-level rise and in SST. Only a minor portion of the accommodation space has been added by subsidence compared to that provided by glacio-eustatic sea-level rise. Accretion rates in reefs dominated by massive corals are statistically similar to accretion rates in reefs dominated by branched corals. While lagoonal background sedimentation rates average 0.89 m/kyr they have been increasing during the past 10 kyr, most probably due to lagoon deepening. Lagoonal background sedimentation rates are insufficient to fill available accommodation space in the examples studied. Lagoonal carbonate sedimentation usually started with a considerable hiatus after marine inundation and mangrove peat formation. Time and flushing appear to be major controlling environmental factors affecting reef consolidation, which is strongest on windward positions and in mid to late Holocene sections, respectively. Reef cements have been quantified and average 8.6% of the reef volume.

ACKNOWLEDGEMENTS

We are very grateful to Bob Ginsburg for suggesting that the authors team up for their first joint drilling project on the Belize atolls. Subsequently, for the past almost 25 years, we have teamed up many more times for coral reef drilling. The Deutsche Forschungsgemeinschaft (DFG, Bonn, Germany) financed most of the field-work. ChevronTexaco (Tony Lomando, San Ramon, USA) supported parts of the drilling on Lighthouse Reef, and the Comparative Sedimentology Laboratory (Gregor Eberli, University of Miami, USA) parts of the coring on Glovers Reef, Belize. Peter Swart (Miami) measured stable isotopes in water samples. Sybille Kleineidam (Tübingen) ran the spectrofluorometer to measure dye concentrations in well water. We are grateful to numerous helpers who have assisted during 10 drilling expeditions over the past 25 years. Two anonymous journal reviewers made helpful comments, which improved this paper.

REFERENCES

Abbey, E., Webster, J. M., Braga, J. C., Sugihara, K., Wallace, C., Iryu, Y., … Seard, C. (2011). Variation in deglacial coralgal assemblages and their paleoenvironmental significance: IODP Expedition 310, "Tahiti Sea Level". *Global and Planetary Change*, *76*, 1–15. https://doi.org/10.1016/j.gloplacha.2010.11.005

Aissaoui, D. M., & Purser, B. H. (1985). Reef diagenesis: Cementation at Mururoa Atoll. *Proceedings 5th International Coral Reef Symposium*, *3*, 257–262.

Blanchon, P., & Perry, C. T. (2004). Taphonomic differentiation of *Acropora palmata* facies in cores from Campeche Bank reefs, Gulf of Mexico. *Sedimentology*, *51*, 53–76. https://doi.org/10.1046/j.1365-3091.2003.00610.x

Camoin, G. F., Seard, C., Deschamps, P., Webster, J. M., Abbey, E., Braga, J. C., … Dussouillez, P. (2012). Reef response to sea-level and environmental changes during the last deglaciation: Integrated Ocean Drilling Program Expedition 310, Tahiti Sea Level. *Geology*, *40*, 643–646. https://doi.org/10.1130/G32057.1

Camoin, G. F., & Webster, J. M. (2015). Coral reef response to Quaternary sea-level and environmental changes: State of the science. *Sedimentology*, *62*, 401–428. https://doi.org/10.1111/sed.12184

Davies, P. J., & Marshall, J. F. (1980). A model for epicontinental reef growth. *Nature*, *287*, 37–38. https://doi.org/10.1038/287037a0

Dechnik, B., Webster, J. M., Davies, P. J., Braga, J. C., & Reimer, P. J. (2015). Holocene "turn-on" and evolution of the southern Great Barrier Reef: Revisiting reef cores from the Capricorn Bunker Group. *Marine Geology*, *363*, 174–190. https://doi.org/10.1016/j.margeo.2015.02.014

DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea level rise. *Nature*, *531*, 591–597. https://doi.org/10.1038/nature17145

Dullo, W. C. (2005). Coral growth and reef growth: A brief review. *Facies*, *51*, 33–48. https://doi.org/10.1007/s10347-005-0060-y

Eyre, B. D., Cyronak, T., Drupp, P., DeCarlo, E. H., Sachs, J. P., & Andersson, A. J. (2018). Coral reefs will transition to net dissolving before the end of century. *Science*, *359*, 908–911. https://doi.org/10.1126/science.aao1118

Fairbanks, R. G. (1989). A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-water circulation. *Nature*, *342*, 637–642. https://doi.org/10.1038/342637a0

Friedman, G. M. (1985). The problem of submarine cement in classifying reef rock: An experience in frustration. In N. Schneidermann & P. M. Harris (Eds.), *Carbonate cements* (pp. 117–121). Tulsa, OK: SEPM Special Publication 36. https://doi.org/10.2110/pec.85.36

Gischler, E. (2003). Holocene lagoonal development in isolated carbonate platforms of Belize. In P. Blanchon & L. Montaggioni (Eds.), *Impact of sea level and climate on Quaternary reef development*. *Sedimentary Geology*, *159*, 113–132.

Gischler, E. (2008). Accretion patterns in Holocene tropical coral reefs: Do massive coral reefs with slowly growing corals accrete faster than branched coral reefs with rapidly growing corals? *International Journal of Earth Sciences*, *97*, 851–859. https://doi.org/10.1007/s00531-007-0201-3

Gischler, E., Hudson, J. H., Humblet, M., Braga, J. C., Eisenhauer, A., Isaack, A., … Camoin, G. F. (2016). Late Quaternary barrier and fringing reef development of Bora Bora (Society Islands, South Pacific): First subsurface data from the Darwin type barrier-reef system. *Sedimentology*, *63*, 1522–1549. https://doi.org/10.1111/sed.12272

Gischler, E., Hudson, J. H., Humblet, M., Braga, J. C., Schmitt, D., Isaack, A., … Camoin, G. F. (2019). Holocene and Pleistocene fringing reef growth and the role of accommodation space and exposure to waves and currents (Bora Bora, Society Islands, south

Pacific). *Sedimentology*, *66*, 305–328. https://doi.org/10.1111/sed.12533

Gischler, E., Hudson, J. H., & Pisera, A. (2008). Late Quaternary reef growth and sea level in the Maldives (Indian Ocean). *Marine Geology*, *250*, 104–113. https://doi.org/10.1016/j.margeo.2008.01.004

Gischler, E., & Lomando, A.J. (2000). Isolated carbonate platforms of Belize, Central America: Sedimentary facies, late Quaternary history and controlling factors. In E. Insalaco, P. W. Skelton, & T. J. Palmer (Eds.), *Carbonate platform systems: Components and interactions*. *Geological Society of London, Special Publication*, *178*, 135-146.

Gischler, E., Lomando, A. J., Hudson, J. H., & Holmes, C. W. (2000). Last interglacial reef growth beneath Belize barrier and isolated platform reefs. *Geology*, *28*, 387–390. https://doi.org/10.1130/0091-7613(2000)28<387:LIRGBB>2.0.CO;2

Hammer, Ø., Harper, D. A. T., & Ryan, P. D. (2001). PAST: Paleontological statistics software package for education and data analysis. *Palaeontologica Electronica*, *4*, 1–9.

Hubbard, D. K. (2009). Depth-related and species-related patterns of Holocene reef accretion in the Caribbean and western Atlantic: A critical assessment of existing models. In P. K. Swart, G. P. Eberli & J. McKenzie (Eds.), *Perspectives in carbonate geology: A tribute to the career of Robert Nathan Ginsburg* (vol. 41) (pp. 1–18). Chichester: Wiley.

Hubbard, D. K., Gill, I. P., & Burke, R. B. (2013). Holocene reef building on eastern St. Croix, US Virgin Islands: Lang Bank revisited. *Coral Reefs*, *32*, 653–669. https://doi.org/10.1007/s00338-013-1041-1

Hubbard, D., Gischler, E., Davies, P., Montaggioni, L., Camoin, G., Dullo, W. C., … Scheffers, S. (2014). Island outlook: Warm and swampy. *Science*, *345*, 1461. https://doi.org/10.1126/science.345.6203.1461-a

Hubbard, D. K., Miller, A. I., & Scaturo, D. (1990). Production and cycling of calcium carbonate in a shelf-edge reef system (St. Croix, U.S. Virgin Islands): Applications to the nature of reef systems in the fossil record. *Journal of Sedimentary Petrology*, *60*, 335–360.

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., … Wilson, S. K. (2017). Global warming and recurrent mass bleaching of corals. *Nature*, *543*, 373–377. https://doi.org/10.1038/nature21707

IPCC (2013). Summary for policymakers. In T. F. Stocker, F. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Migley (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the International Panel on Climate Change* (pp. 3–29). Cambridge, UK: Cambridge University Press.

Isaack, A., Gischler, E., Hudson, J. H., Anselmetti, F. S., Lohner, A., Garbode, E., & Camoin, G. F. (2016). A new model evaluating sediment dynamics throughout the Holocene: Insights from a mixed carbonate-siliciclastic lagoon (Bora Bora, Society Islands, French Polynesia, South Pacific). *Sedimentary Geology*, *343*, 99–118. https://doi.org/10.1016/j.sedgeo.2016.08.002

James, N. P., Ginsburg, R. N., Marszalek, D. S., & Choquette, P. W. (1976). Facies and fabric specificity of early subsea cements in shallow Belize (British Honduras) reefs. *Journal of Sedimentary Petrology*, *46*, 523–544.

Kiene, W. E., & Hutchings, P. (1994). Bioerosion experiments at Lizard Island, Great Barrier Reef. *Coral Reefs*, *13*, 91–98. https://doi.org/10.1007/BF00300767

Kim, W., Fouke, B., Quinn, T., Kerans, C., & Taylor, F. (2012). Sea-level rise, depth-dependent carbonate sedimentation and the paradox of drowned reefs. *Sedimentology*, *59*, 1677–1694. https://doi.org/10.1111/j.1365-3091.2012.01321.x

Kleypas, J. A., Buddemeier, R. W., Archer, D., Gattuso, J. P., Langdon, C., & Opdyke, B. N. (1999). Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science*, *284*, 118–120. https://doi.org/10.1126/science.284.5411.118

Klostermann, L., & Gischler, E. (2015). Holocene sedimentary evolution of a mid-ocean atoll lagoon, Maldives, Indian Ocean. *International Journal of Earth Sciences*, *104*, 289–307. https://doi.org/10.1007/s00531-014-1068-8

Lighty, R. G., Macintyre, I. G., & Stuckenrath, R. (1978). Submerged early Holocene barrier reef south-east Florida shelf. *Nature*, *276*, 59–60. https://doi.org/10.1038/276059a0

Marcott, S. A., Shakun, J. D., Clark, P. U., & Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11,300 years. *Science*, *339*, 1198–1201. https://doi.org/10.1126/science.1228026

Marshall, J. F. (1985). Cross-shelf and facies related variations in submarine cementation in the central Great Barrier Reef. *Proceedings 5th International Coral Reef Symposium*, *3*, 221–226.

Marshall, J. F., & Davies, P. J. (1981). Submarine lithification on windward reef slopes: Capricorn-Bunker Group, southern Great Barrier Reef. *Journal of Sedimentary Petrology*, *51*, 953–960.

Montaggioni, L. F. (2005). History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors. *Earth-Science Reviews*, *71*, 1–75. https://doi.org/10.1016/j.earscirev.2005.01.002

Neumann, A. C., & Macintyre, I. G. (1985). Reef response to sea level rise: Keep-up, catch-up or give-up. *Proceedings 5th International Coral Reef Symposium*, *3*, 105–110.

Pala, C. (2014). Warming may not swamp islands. *Science*, *345*, 496–497. https://doi.org/10.1126/science.345.6196.496

Pandolfi, J. M., Bradbury, R. H., Sala, E., Hughes, T. P., Bjorndal, K. A., Cooke, R. G., … Jackson, J. B. C. (2003). Global trajectories of the longterm decline of coral reef ecosystems. *Science*, *301*, 955–958. https://doi.org/10.1126/science.1085706

Pandolfi, J. M., Connolly, S. R., Marshall, D. J., & Cohen, A. L. (2011). Projecting coral reef futures under global warming and ocean acidification. *Science*, *333*, 418–422. https://doi.org/10.1126/science.1204794

Perry, C. T., Alvarez-Filip, L., Graham, N. A. J., Mumby, P. J., Wilson, S. K., Kench, P. S., … Macdonald, C. (2018). Loss of coral reef growth capacity to track future increases in sea level. *Nature*, *558*, 396–400.https://doi.org/10.1038/s41586-018-0194-z

Pigott, J. D., & Land, L. S. (1986). Interstitial water chemistry of Jamaican reef sediment: sulfate reduction and submarine cementation. *Marine Chemistry*, *19*, 355–378. https://doi.org/10.1016/0304-4203(86)90056-3

van der Plas, L., & Tobi, A. C. (1965). A chart for judging the reliability of point counting results. *American Journal of Science*, *263*, 87–90. https://doi.org/10.2475/ajs.263.1.87

Purdy, E. G. (1974). Reef configurations: cause and effect. In L. F. Laporte (Ed.), *Reefs in time and space* (vol. 18) (pp. 9–76). Tulsa: SEPM Special Publication.

Purdy, E. G., & Gischler, E. (2005). The transient nature of the empty bucket model of reef sedimentation. In J. J. G. Reijmer & A. Immenhauser (Eds.), *Sedimentology in the 21st century – a tribute to Wolfgang Schlager*. *Sedimentary Geology*, *175*, 35-47.

Purdy, E. G., & Winterer, E. L. (2001). Origin of atoll lagoons. *GSA Bulletin*, *113*, 837–854.

Reid, R. P., Macintyre, I. G., & James, N. P. (1990). Internal precipitation of microcrystalline carbonate: A fundamental problem for sedimentologists. *Sedimentary Geology*, *68*, 163–170. https://doi.org/10.1016/0037-0738(90)90109-7

Schlager, W. (1981). The paradox of drowned reefs and carbonate platforms. *GSA Bulletin*, *92*, 197–211. https://doi.org/10.1130/0016-7606(1981)92<197:TPODRA>2.0.CO;2

Schlager, W., & Purkis, S. J. (2013). Bucket structure in carbonate accumulations of the Maldive, Chagos and Laccadive archipelagoes. *International Journal of Earth Sciences*, *102*, 2225–2238. https://doi.org/10.1007/s00531-013-0913-5

Schultz, S., Gischler, E., & Oschmann, W. (2010). Diversity, distribution, and assemblages of benthic foraminifera in atoll lagoons during the Holocene, Belize, Central America. *Facies*, *56*, 323–336. https://doi.org/10.1007/s10347-010-0217-1

Scoffin, T. P. (1992). Taphonomy of coral reefs: A review. *Coral Reefs*, *11*, 57–77. https://doi.org/10.1007/BF00357423

Scoffin, T. P. (1993). Microfabrics of carbonate muds in reefs. In R. Rezak, & D. L. Lavoie (Eds.), *Carbonate microfabrics* (pp. 65–74). New York, NY: Springer. https://doi.org/10.1007/978-1-4684-9421-1

Stott, L., Cannariato, K., Thunell, R., Haug, G. H., Koutavas, A., & Lund, S. (2004). Decline of surface temperatures and salinity in the western tropical Pacific Ocean in the Holocene epoch. *Nature*, *431*, 56–59. https://doi.org/10.1038/nature02903

Tipper, J. C. (1997). Modeling carbonate platform sedimentation – lag comes naturally. *Geology*, *25*, 495–498. https://doi.org/10.1130/0091-7613(1997)025<0495:MCPSLC>2.3.CO;2

Toth, L. T., Kuffner, I. B., Stathakopoulos, A., & Shinn, E. A. (2018). A 3,000-year lag between the geological and ecological shutdown of Florida's coral reefs. *Global Change Biology*, *24*, 5471–5483. https://doi.org/10.1111/gcb.14389

Tucker, M. E., & Wright, V. P. (1990). *Carbonate sedimentology*. London, UK: Blackwell, 482 pp. https://doi.org/10.1002/9781444314175

Vogel, K., Gektidis, M., Golubic, S., Kiene, W. E., & Radtke, G. (2000). Experimental studies on microbial erosion at Lee Stocking Island, Bahamas and One Tree Island, Great Barrier Reef, Australia: Implications for paleoecological reconstructions. *Lethaia*, *33*, 190–204.

Webster, J. M., Braga, J. C., Humblet, M., Potts, D. C., Iryu, Y., Yokoyama, Y., … Logheed, B. C. (2018). Response of the Great Barrier Reef to sea-level and environmental changes over the past 30,000 years. *Nature Geoscience*, *11*, 426–432. https://doi.org/10.1038/s41561-018-0127-3

Woodruff, J. D., Irish, J. L., & Camargo, J. (2013). Coastal flooding by tropical cyclones and sea-level rise. *Nature*, *504*, 44–52. https://doi.org/10.1038/nature12855

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Gischler E, Harold Hudson J. Holocene tropical reef accretion and lagoon sedimentation: A quantitative approach to the influence of sea-level rise, climate and subsidence (Belize, Maldives, French Polynesia). *Depositional Rec*. 2019;5:515–539. https://doi.org/10.1002/dep2.62