Quaternary Science Reviews 77 (2013) 181–189

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Reconstructing mid-late Holocene cyclone variability in the Central Pacific using sedimentary records from Tahaa, French Polynesia

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ARTICLE INFO

Article history:
Received 7 March 2013
Received in revised form
13 July 2013
Accepted 15 July 2013
Available online 24 August 2013

Keywords:
Tropical cyclones
South Pacific
ENSO
Precession

ABSTRACT

We lack an understanding of the geographic and temporal controls on South Pacific cyclone activity. Overwash records from backbarrier salt marshes and coastal ponds have been used to reconstruct tropical cyclone strikes in the North Atlantic basin. However, these specific backbarrier environments are scarce in the South Pacific, with cyclone records limited primarily to the period of modern observation. This instrumental record suggests a correlation with the El Niño–Southern Oscillation (ENSO), but longer records are necessary to test this relationship over geologic timescales and explore other potential climate drivers of tropical cyclone variability. Deep lagoons behind coral reefs are widespread in the Pacific and provide an alternative setting for developing long-term sedimentary reconstructions of tropical cyclone occurrence. Coarse-grained event deposits within the sediments of a back-reef lagoon surrounding Tahaa reveal a 5000-year record of cyclone occurrences. Timing of recent high-energy deposits matches well with observed tropical cyclone strikes and indicates coarse deposits are storm derived. Longer records show tropical cyclone activity was higher from 5000 to 3800 and 2900 to 500 yrs BP. Comparison to records from the North Pacific (out-of-phase) and North Atlantic (in phase) suggests a coordinated pattern of storm activity across tropical cyclone basins over the mid-late Holocene. The changes in tropical cyclone activity we observe in the South Pacific and across other basins may be related to ENSO as well as precession driven changes in ocean-atmosphere thermal gradients.

1. Introduction

Historical cyclone records are scarce for French Polynesia, owing to the poor spatial coverage of populated islands and low ship traffic in the central South Pacific. Satellite monitoring since 1970 AD has greatly improved storm detection, yet the shortage of observations prior to this instrumental era limits our understanding of the environmental forcings driving long-term patterns in tropical cyclone activity within the basin.

On seasonal to annual time-scales, instrumental observations show that the El Niño-Southern Oscillation (ENSO) exerts significant control over tropical cyclone activity in the South Pacific (Revell and Goulter, 1986; Hastings, 1990; Basher and Zheng, 1995). Analysis of tropical cyclone genesis locations between 1939 and 1979 AD by Revell and Goulter (1986) revealed a northeastern (southwestern) displacement during El Niño (La Niña). The eastward shift in cyclone origin locations during El Niños follows the migration of South Pacific Convergence Zone (SPCZ) and the establishment of favorable atmospheric conditions over French Polynesia (Revell and Goulter, 1986). These conditions do not significantly change the overall frequency of storms in the western/central South Pacific (Hastings, 1990).

On longer-timescales, changes in insolation may also be influencing tropical cyclone frequency in the South Pacific. Modeling efforts by Korty et al. (2012) suggest that decreased storm season insolation during the mid-Holocene due to precession may have led to a steeper atmospheric thermal gradient and increased potential intensity in the South Pacific. However, precession driven changes in insolation are also thought to have limited El Niño-like variability during the mid-Holocene (Clement et al., 2000), possibly restraining tropical cyclone activity in the Central Pacific. Longer records are needed to resolve the relative influence of these competing factors on tropical cyclone variability.

Backbarrier beach overwash records have been successfully used to extend records of tropical cyclone landfalls in the North

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http://dx.doi.org/10.1016/j.quascirev.2013.07.019

Atlantic (Liu and Fearn, 1993; Donnelly et al., 2001; Donnelly and Woodruff, 2007; Scileppi and Donnelly, 2007; Lane et al., 2011; Toomey et al., 2013) and in the North Pacific (Woodruff et al., 2009). Overwash deposits are formed when storm waves and surge over-top the barrier beach, moving sediment into the back-barrier setting. Deposition of coarser barrier beach derived material in the otherwise low-energy back-barrier environments provides a diagnostic signal. Likewise, deposition of coarse reef material in back-reef lagoons may serve as a similar proxy for tropical cyclone strikes and represent an unexplored archive of long-term storm activity. Under fair-weather conditions, wave energy typically dissipates within 100–500 m of the reef crest (Kench and Brander, 2006), limiting transport of coarse reef sediment (halimeda and coral) into the lagoon. However, large waves and storm surge during cyclone strikes may provide a key pathway for deposition of coarse layers in otherwise mud-rich deep lagoons.

Mobilization of barrier reef material, lagoon-ward transport and deposition in the back-barrier has been widely documented (summarized by Harmelin-Vivien (1994)) during modern tropical cyclones. In particular, Harmelin-Vivien and Laboute (1986) noted development of boulder ramparts on at Moorea and Tikehau Atoll, during the 1982/1983 cyclone season during which six storms threatened French Polynesia. A survey of Jaluit Atoll (Marshall Islands) following typhoon Ophelia (1958 AD) revealed large-scale erosion of reef material and deposition of rubble ridges on the reef flat (Blumenstock, 1958; Blumenstock et al., 1961) and coarse-grained sediment in the lagoon (McKee, 1959). Excavation of this deposit (Curray et al., 1970) revealed three earlier conglomerates dating to the late Holocene.

Geomorphic evidence of mid-late Holocene tropical cyclone activity in the Pacific, including coral conglomerates, is well documented in the literature (Table 1). Beach ridge formation in Northeastern Australia has also been attributed to large storms over the past several thousand years (Forsyth et al., 2010, 2012; Nott and Forsyth, 2012).

Here we provide a description of sediments collected from a back-barrier reef lagoon on Tahaa, French Polynesia. Preserved coarse-grained deposits are found to be a viable proxy of cyclone occurrence and provide one of the first reconstructions of tropical cyclone activity for the central South Pacific. The reconstruction is employed to address the following key questions: (1) How has tropical cyclone activity around French Polynesia changed over the mid-late Holocene, (2) is there a clear relationship between ENSO and cyclone frequency in the central South Pacific prior to the instrumental era and (3) what are the effects of different climatic regimes (e.g. ENSO, Precession) on central South Pacific cyclone activity?

2. Study site

Tahaa (16° S 151° W) is located 225 km northwest of Tahiti and is the smaller remnant of a double-coned volcanic shield formed 2–3 Ma (Guillou et al., 2005). Tahaa is closely neighbored by the island of Raiatea, 6 km to the south (Fig. 1). The barrier-reef system surrounding Tahaa follows a characteristic sequence of environs and depositional settings. In general, a 30–40 m deep lagoon is protected by a broad 1–2 km wide reef flat and narrow 50–100 m wide barrier reef. Our study site is located on the western side of the lagoon separating Tahaa and Raiatea (Fig. 1).

Reliable instrumental data for the central South Pacific begins in 1961 AD (International Best Track Archive for Climate Stewardship—IBTrACS) (Knapp et al., 2010). Since the onset of this record eight tropical storms (Australian Scale) have passed within 110 km (approximately the scale of tropical cyclone strength winds and defined TC 'strike') of Tahaa (Fig. 1), with these modern events providing a means for calibrating a cyclone proxy from Tahaa sediments. Of the eight tropical storms impacting the site since 1961 AD, only three had winds speeds in excess of 34 knots (10-min sustained winds). These include Cyclone Lisa in 1983 AD as a category 1 storm, and Cyclone Rewa in 1983 AD and Cyclone Osea in 1997 AD, both category 3 storms.

Prior to the best-track data set, historic archives document 14 tropical cyclones affected the Society Islands between 1825 and 1966 AD (Teissier, 1982). Of these, detailed accounts of only the 1878, 1903, 1905 and 1906 AD storms exist and given the lack of direct meteorological observations, the intensity, path and overall impact of historic events at our site remain unclear. Efforts to extend or improve these records using geologic proxies have so far been limited.

Geologic reconstructions of overwash occurrences for French Polynesia are restricted to dated reef blocks and coral conglomerate deposits along reef flats. Thirteen reef blocks or conglomerate deposits thrust onto the reef flat during past storm events have been identified on Tahaa and nearby islands (within 110 km of Tahaa: Raiatea, Bora Bora (~30 km NW), Tupai (~60 km NW), Maupiti (~85 km NW), Table 1). Radiocarbon dating of this over-washed material revealed calibrated ages between 920 and 4405 yrs BP, with reef conglomerate deposits on Tahaa and Raiatea dating to 2715 and 4405 yrs BP. The small number of events within these records limits characterization of higher frequency patterns, however, they provide a valuable data set for cross calibration of higher resolution, continuous reconstructions from the lagoonal sediments of Tahaa.

3. Methods

To reconstruct the overwash history preserved in the lagoonal sediments of Tahaa we acquired high-resolution seismic profiles and 26 vibracores aboard the *S.S.V. Robert C. Seamans* between the 10th and 20th of January 2009. Sub-bottom stratigraphy was mapped using a Benthos CHIRP-II, sweeping a bandwidth range of 2–7 kHz. Low signal attenuation in the lagoon sediments allowed for penetration of over 30 m. Post-processing of seismic data in Kingdom Suite 8.4 (Seismic Microtechnology INC) allowed for identification of core sites with thick depositional sequences close to the barrier where susceptibly to overwash is the greatest.

Coring was carried out using a Rossfelder P-3 underwater vibracore. Following recovery, cores were sectioned and shipped to the Woods Hole Oceanographic Institution for further processing. There, each core was split and refrigerated in order to prevent drying prior to analysis. Major transitions in color, grain size and organic content were identified and used to select TAH VC3 and TAH VC4 for more detailed analyzes of storm overwash. Overwash events in TAH VC3 and TAH VC4 were identified by increases in particle size. Each core was contiguously sampled at 1 cm resolution. For an improved modern calibration the top 25 cm of TAH VC3 was sampled at a higher resolution of 1/2 cm. Following subsampling, sediments were heated at 100 °C for 5 h and weighed to obtain their dry mass. Coarse material was then separated using standard 63 μm, 250 μm and 2 mm sieves.

Age constraints in the cores were obtained using both ^{210}Pb and radiocarbon dating (Figs. 2 and 3). Standard ^{210}Pb methods were used to establish chronology: (1) bulk subsamples were dried and homogenized before counting on a Canberra germanium well detector, with ^{210}Pb activity computed using gamma spectroscopy of the 46.54 keV photopeak and (2) ^{210}Pb chronology was determined assuming a constant initial concentration model (CIC) with supported ^{210}Pb defined by activities at depth (Appleby and Oldfield, 1978, 1983). Radiocarbon dating was used to determine a chronology in each core below the detection limit of excess ^{210}Pb, with

Table 1
Compilation of central South Pacific coral conglomerate and reef block deposits from the literature. Dates highlighted in gray were corrected for ^{13}C fractionation based on dating/correction information available for each entry or correspondence with authors. Direction arrow, indicates the orientation of the island where the deposit was found. Age reported is the date given in the literature. The maximum probability peak age takes into account reservoir effect (400 yrs), fractionation and the Marine09 calibration curve. More information on many of these samples is summarized in Pirazzoli and Montaggioni, 1988. Note: Gif_6561 was found stratagraphically out of order.

Group	Island	↗	Lab code	Age reported (yrs BP)	Age error (yrs BP)	Max prob peak (yrs BP)	Dated material	Ref
Society	Manuae	NE	Gif_6414	2640	60	2790	Conglomerate (Calcirudite)	Pirazzoli, 1985b
	Maupiti	NE	Gif_6087	2700	80	2860	Reef Block (Porites Lobata)	Pirazzoli, 1985b
	Maupiti	NW	Gif_6563	2200	60	2300	Conglomerate (Calcarenite)	Pirazzoli, 1985b
	Tupai	NW	Gif_6411	1950	60	1970	Reef Block	Pirazzoli, 1985b
	Tupai	NW	Gif_6409	1740	60	1720	Reef Block	Pirazzoli, 1985b
	Tupai	E	Gif_6505	2910	60	3165	Conglomerate	Pirazzoli, 1985b
	Tupai	E	Gif_6506	2780	60	2965	Conglomerate	Pirazzoli, 1985b
	Bora Bora	N	Gif_6562	2500	60	2700	Conglomerate	Pirazzoli, 1985b
	Bora Bora	N	Gif_893	2250	130	2330	Reef Block	Guilcher, 1969; Pirazzoli, 1985b
	Bora Bora	N	Gif_6916	1650	50	1610	Conglomerate	Pirazzoli and Montaggioni, 1988
	Bora Bora	N	Gif_6915	1950	50	1970	Conglomerate	Pirazzoli and Montaggioni, 1988
	Bora Bora	N	Gif_6561	980	50	920	Conglomerate	Pirazzoli, 1985b
	Raiatea	E	Gif_6097	3880	80	4405	Conglomerate (Porites)	Pirazzoli, 1985b
	Tahaa	N	Gif_6917	2530	60	2715	Conglomerate	Pirazzoli and Montaggioni, 1988
	Moorea	E	Gif_6100	2670	60	2835	Conglomerate (Calcirudite)	Montaggioni and Pirazzoli, 1984; Pirazzoli, 1985b
	Moorea	E	Gif_6099	2320	60	2395	Conglomerate (Calcirudite)	Montaggioni and Pirazzoli, 1984; Pirazzoli, 1985b
	Moorea	E	Gif_6098	2690	70	2850	Conglomerate (Calcarenite)	Montaggioni and Pirazzoli, 1984; Pirazzoli, 1985b
	Moorea	NE	Gak_9974	6070	130	6725	Conglomerate (Acropora)	Montaggioni and Pirazzoli, 1984
	Moorea	NW	Gif_3880	2280	100	2340	Conglomerate	Chevalier and Salvat, 1976; Pirazzoli, 1985b
	Moorea	E	Gak_9975	3340	120	3430	Conglomerate (Calcirudite)	Montaggioni and Pirazzoli, 1984
	Tahiti	NW	Gif_6101	2610	60	2760	Coglomerate	Pirazzoli, 1985b
	Tahiti	NE	Gif_6103	110	60	130	Conglomerate (Framework)	Pirazzoli, 1985b
	Tahiti	N	Gif_6102	3660	60	4085	Conglomerate (Framework)	Pirazzoli, 1985b
	Tahiti Iti	N	Gif_6104	2850	60	3070	Conglomerate (Calcirudite)	Pirazzoli, 1985b
Tuamotu	Mataiva	S	Gak_9970	5420	110	5990	Conglomerate (Porites)	Montaggioni and Pirazzoli, 1984; Pirazzoli and Montaggioni, 1986
	Mataiva	SW	Gak_9971	5230	140	5840	Conglomerate	Montaggioni and Pirazzoli, 1984; Pirazzoli and Montaggioni, 1986
	Mataiva	SW	Gak_9972	3470	120	3580	Conglomerate	Montaggioni and Pirazzoli, 1984; Pirazzoli and Montaggioni, 1986
	Rangiroa	NE	HV_12282	705	65	660	Conglomerate	Pirazzoli, 1985a; Pirazzoli and Montaggioni, 1986
	Rangiroa	Lagoon	HV_12283	2775	60	2960	Conglomerate	Pirazzoli, 1985a; Pirazzoli and Montaggioni, 1986
	Rangiroa	NE	LJ_1372	4900	300	5465	Conglomerate	Hubbs and Bien, 2006
	Arutua	SE	HV_12280	1380	70	1310	Conglomerate	Pirazzoli and Montaggioni, 1986
	Arutua	SE	HV_12281	1565	65	1520	Conglomerate	Pirazzoli and Montaggioni, 1986
	Apataki	SW	HV_12278	3135	65	3415	Conglomerate	Pirazzoli and Montaggioni, 1986
	Apataki	SW	HV_12279	2990	130	3265	Conglomerate	Pirazzoli and Montaggioni, 1986
	Apataki	SW	HV_12277	1580	70	1530	Conglomerate	Pirazzoli and Montaggioni, 1986
	Takapoto	E	Gak_9976	5020	140	5580	Conglomerate	Montaggioni and Pirazzoli, 1984; Pirazzoli and Montaggioni, 1986
	Takapoto	SW	HV_12276	1320	80	1275	Conglomerate	Montaggioni and Pirazzoli, 1984; Pirazzoli and Montaggioni, 1986
	Takapoto	SW	HV_12275	1580	70	1530	Conglomerate	Montaggioni and Pirazzoli, 1984; Pirazzoli and Montaggioni, 1986
	Hikueru	NW	HV_13015	1470	60	1400	Reef Block	Pirazzoli et al., 1988
	Pukarua	NW	HV_13021	3875	70	4400	Conglomerate	Pirazzoli et al., 1988
	Vahitahi	W	Pa_162	3960	110	4500	Conglomerate	Pirazzoli et al., 1987
	Mururoa	E	Gig_631	5550	300	6180	Conglomerate	Delibrias et al., 1969
	Hao	NE	Gif_1667	3300	100	3615	Conglomerate	Pirazzoli et al., 1988
	Nukutavake	NW	HV_13010	1925	50	1935	Reef Block	Pirazzoli et al., 1988
	Vairaatea	NW	HV_13014	3995	65	4525	Reef Block	Pirazzoli et al., 1988
	Tureia	N	HV_13001	1220	65	1180	Reef Block	Pirazzoli et al., 1988
Gambier	Mangareva	N	HV_12264	3035	95	3325	Conglomerate	Pirazzoli and Montaggioni, 1987
	Mangareva	N	HV_12263	2815	100	3025	Conglomerate	Pirazzoli and Montaggioni, 1987
	Mangareva	NW	HV_12262	1260	65	1235	Conglomerate	Pirazzoli and Montaggioni, 1987
	Temoe	NE	HV_12266	3170	60	3450	Conglomerate (Pebble)	Pirazzoli, 1987; Pirazzoli and Montaggioni, 1987
	Temoe	N	HV_12267	3405	85	3755	Conglomerate (Pebble)	Pirazzoli, 1987
	Temoe	N	HV_12268	2875	75	3125	Conglomerate (Pebble)	Pirazzoli, 1987
	Temoe	W	HV_12269	3145	95	3430	Conglomerate (Shell)	Pirazzoli, 1987
Austral	Tubuai	NE	HV_13005	1400	55	1330	Conglomerate	Pirazzoli and Montaggioni, 1988

(*continued on next page*)

Table 1 (*continued*)

Group	Island	↗	Lab code	Age reported (yrs BP)	Age error (yrs BP)	Max prob peak (yrs BP)	Dated material	Ref
Cook	Suwarrow	NW	NZ_6102	2000	60	2045	Conglomerate (Porites)	Woodroffe et al., 1990
	Suwarrow	NW	NZ_6104	4460	50	5235	Conglomerate (Porites)	Woodroffe et al., 1990
	Suwarrow	NE	NZ_6100	3560	50	3965	Conglomerate (Porites)	Woodroffe et al., 1990
	Suwarrow	NE	NZ_6109	2620	50	2770	Conglomerate (Porites)	Woodroffe et al., 1990
	Suwarrow	NE	NZ_6111	3630	50	4070	Conglomerate	Woodroffe et al., 1990

samples analyzed at the National Ocean Science Accelerator Mass Spectrometry Facility (NOSAMS) in Woods Hole, Massachusetts. Standard methods were used for dating bulk organic carbon, while continuous flow gas bench methods (von Reden et al., 2012) were employed to date bulk carbonate material (Table 2). Radiocarbon ages were calibrated in Matlab using procedures outlined for CALIB 6.0 (Reimer et al., 2009), with a standard marine correction applied to the bulk carbonate samples. Best-fit linear sedimentation rates were used to set the age model for each core (below 210Pb chronology).

Coral conglomerate and reef block ^{14}C ages from the literature (Table 1) were reported in an effort to provide an independent test of storm activity across the entire cyclone basin. Observations were first compiled and then standardized using Marine09 (Reimer et al., 2009) and a 400 yr marine reservoir. Older dates were also corrected for ^{13}C fractionation (highlighted in gray). The resulting probability distributions and age uncertainties for each event were then used to determine the likely number of events in 250 yr windows. A similar exercise was carried out for the beach ridge deposits (Optically simulated luminescence (OSL) dated) reported for Northeastern Australia (Forsyth et al., 2010, 2012; Nott and Forsyth, 2012) but in this case age errors were assumed to be normally distribution.

In addition to the study's sedimentary reconstructions, the potential correlation between ENSO and storminess in the Society Islands during the satellite era (1970–2009 AD) was also tested for its statistical significance using methods similar to those of Revell and Goulter (1986). The genesis locations of storms in the central South Pacific in the Best Track Archive for Climate Stewardship extends as far back as 1907 AD (IBTrACS (Knapp et al., 2010)). However, statistical analyses are restricted to more accurate data from the satellite era (>1970 AD), with the Pearson's product-

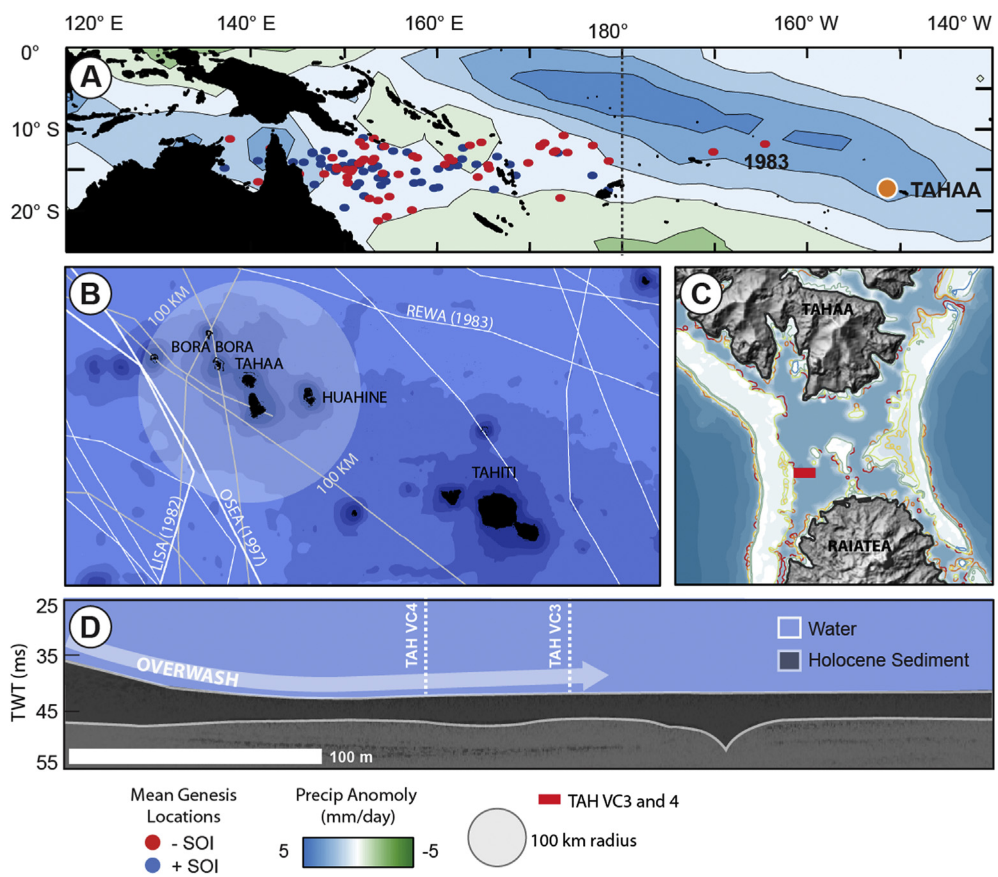

Fig. 1. Site location, geomorphology and local bathymetry. (**A**) Map showing annual mean genesis locations in the South Pacific relative to modes of SOI: positive (blue circle) and negative (red circle). Location of Tahaa is shown by orange dot. Background colors indicate storm season (NDJF) precipitation anomalies for periods of negative SOI (CPC Merged Analysis of Precipitation). (**B**) Cyclone tracks from the IBTrACs data set. Storms passing within 100 km at ≥CAT 1 strength (>34 knots 10-min maximum sustained wind; Lisa (1982); Osea (1997)) are given by thick white line. Less intense storms passing within 100 km are shown by gray lines. Tracks of all other storms are drawn in thin white lines. Rewa (CAT 3) passed within approximately 105km of our site. (**C**) Bathymetric and shaded relief map of Tahaa and Raiatea. Location of core sites for tropical cyclone (TAH VC3 and TAH4) reconstructions are given by the red line. White and light blue areas show barrier reef and reef flat areas. (**D**) Seismic profile across coring site. White dashed lines indicate the location of TAH VC4 and TAH VC3. Holocene sediments are highlighted in dark gray while material interpreted as older Pleistocene sediments are shown in light gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

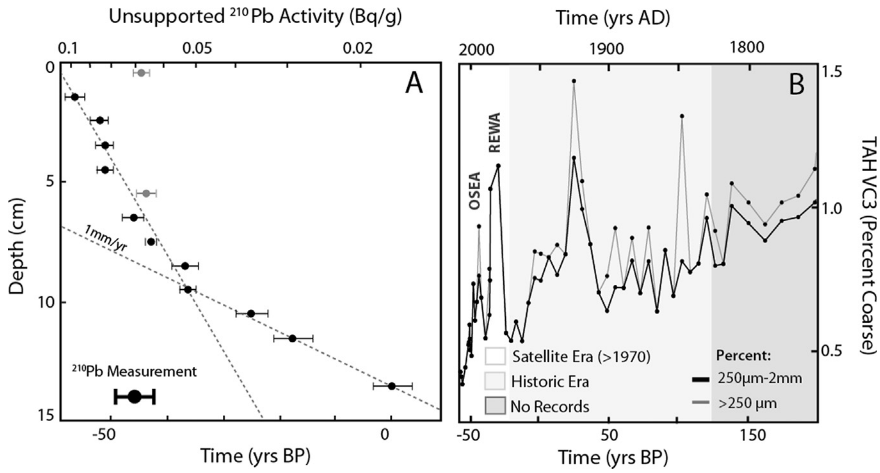

Fig. 2. Chronology and grain-size from TAH VC3 core-top. (A) Unsupported ^{210}Pb chronology. Chronology was interpolated using an initial concentration model and the black data points showing the unsupported ^{210}Pb (no reversals). Note activity increases from right to left in plot. Supported ^{210}Pb was approximately 0.065 (Bq/g). (B) Comparison of historic storm events to coarse grained deposition in TAH VC3. White area highlights satellite era (present–1970 AD). Light gray shows the historic interval (1970–1831 AD). No cyclone record exists prior to 1831 AD (dark gray).

moment correlation test used to quantitatively evaluate the connection between mean genesis location of a storm season and the year's corresponding Southern Oscillation Index value (SOI, Climate and Global Dynamics Division, National Center for Atmospheric Research (NCAR)).

4. Results

4.1. Statistical analyses of modern storms

Fig. 1A presents the annual mean genesis locations in the South Pacific relative to modes of SOI with the Pearson's product-moment test revealing a statistically significant correlation. During periods when SOI was negative storms formed further North ($r = -0.5$; $p < 0.001$) and East ($r = -0.5$; $p = 0.001$) likely driven by migrations of the South Pacific Convergence Zone (SPCZ) (Revell and Goulter, 1986). This analysis is therefore consistent with SOI driving changes in the location of storm formation, although the number of storms in a given cyclone season was not as strongly related to SOI ($r = -0.3216$; $p < 0.05$).

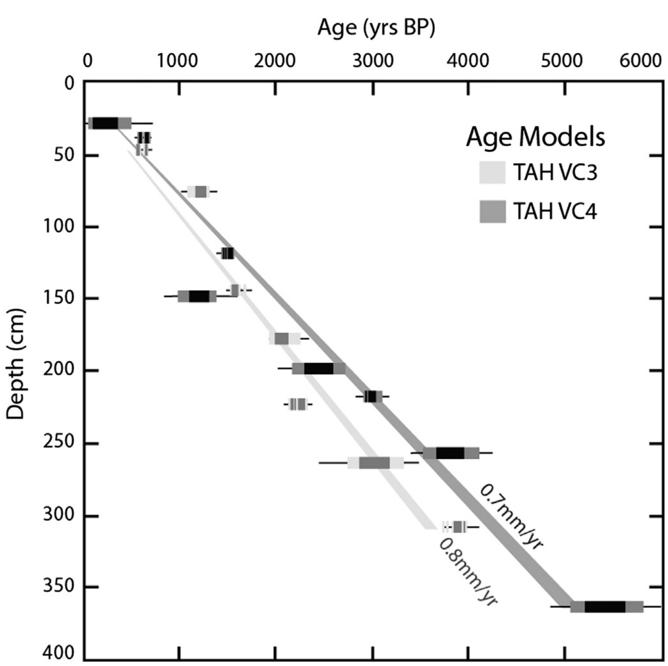

Fig. 3. Radiocarbon chronologies for TAH VC3 (light gray) and TAH VC4 (dark gray). Each bar represents an individual radiocarbon date. Darker inner bars show 1σ ranges. 2σ ranges are given by lighter shaded bars. Black line shows range of ages generated iteratively (1000 times) resampling the probability distribution for each date. Shaded area (TAH VC3: light gray; TAH VC4: dark gray) shows one standard deviation window (based on resampling procedure) around mean sedimentation rate.

4.2. Chronology

Measured ^{210}Pb activity indicates supported levels of 0.065 (Bq/g). Unsupported ^{210}Pb activity is indistinguishable from this background below 14 cm. Above this, our ^{210}Pb profile indicates accumulation rates increased substantially between 1970 and 1990 AD (Fig. 2A). A similar pattern of ^{210}Pb activity was observed on Tahiti and related to increased anthropogenic disturbance (Harris et al., 2001). Additionally, bleaching events in recent years have caused widespread damage to reefs in the Society Islands (Gleason, 1993) as well as around the Pacific (Glynn, 1984) and may have led to increased degradation of the reef and sediment supply to the lagoon. Prior to 1970 AD, ^{210}Pb suggest an accumulation rate of approximately 1 mm/yr, consistent with long-term sedimentation

Table 2
List of radiocarbon dates and ages. Bulk organic samples were dated using conventional AMS methods (highlighted in gray). Bulk carbonate material was dated using continuous flow, gas bench methods.

Core	Depth (cm)	^{14}C age	Error	Material
TAH VC3	47–48	655	25	Bulk organic
TAH VC3	77–78	1659	54	Bulk $CaCO_3$
TAH VC3	146–147	1680	25	Bulk organic
TAH VC3	180–181	2434	51	Bulk $CaCO_3$
TAH VC3	226–227	2200	35	Bulk organic
TAH VC3	266–267	3208	125	Bulk $CaCO_3$
TAH VC3	311–313	3590	35	Bulk organic
TAH VC4	29–30	576	142	Bulk $CaCO_3$
TAH VC4	39–40	565	40	Bulk organic
TAH VC4	119–120	1560	25	Bulk organic
TAH VC4	149–150	1606	101	Bulk $CaCO_3$
TAH VC4	199–200	2675	102	Bulk $CaCO_3$
TAH VC4	219–220	2850	30	Bulk organic
TAH VC4	259–260	3828	109	Bulk $CaCO_3$
TAH VC4	364–365	5095	150	Bulk $CaCO_3$

rates (TAH VC3 = 0.8 mm/yr, TAH VC4 = 0.7 mm/yr) based on radiocarbon results (Fig. 3) given the expected effect of compaction deeper in the sediment column. Seismic surveying indicates relatively uniform sediment thickness (~5 m) and accumulation rates throughout the lagoon separating Tahaa and Raiatea. However, slightly higher lagoonal accumulation rates appear to occur proximal to the reef flat and in local depressions or channels (Fig. 1D).

4.3. Sedimentology

TAH VC3 and VC4 are composed of fine gray aragonite rich mud with only minor shifts in sediment color and composition. Observable organic deposition is limited to the uppermost section of each core, which show streaking of brown mud. Mollusk shells, polychaete tube fragments, coral clasts, foraminifera and other reef derived material make up the coarse fraction (>63 μm), a finding consistent with observation elsewhere in the Leeward Society Islands (Gischler, 2011). Grain-size is very coarse (median grain size or d50 ≅ 500 μm) on the reef flat but decreases rapidly (d50 ≅ 30–25 μm) moving landward in the lagoon (e.g. TAH VC4/VC3).

Comparison of recent coarse-grained deposition with modern cyclone events reveals a strong correspondence (Fig. 2B). The timing of two coarse fraction peaks from the top of TAH VC3 matches with the observed passage of tropical cyclones Rewa (1983, Category 3), Lisa (1983, Category 1) and Osea (1997, Category 3), the strongest events of the instrumental era for this site.

Sedimentary records from Tahaa (TAH VC3 and TAH VC4) also reveal substantial variability in grain size over the Holocene (Fig. 4), as well as different trends for percent coarse (>250 μm and 250 μm to 2 mm) relative to the fraction of very fine to fine sand (i.e. 63–250 μm). Gradual trends dominate within the finer sand fraction (63–250 μm, Fig. 4A) and are largely independent from the event stratigraphy derived from coarser material (i.e. >250 μm). The percent of fine sand in TAH VC4 decreases rapidly from >20 percent at 5000 yrs BP to 10 percent by 3500 yrs BP before tapering to 7 percent at 2500 yrs BP. The fine sand fraction then increases slightly from 1500 to 1000 yrs BP followed by a relatively stable percentage of just above 10 percent over the last 1000 yrs. In comparison, background fractions of percent coarse (as defined by the fraction >250 μm and 250 μm to 2 mm) remain relatively steady through time, with abrupt and isolated peaks becoming more dominate features within these time-series. Two prominent intervals of elevated peaks in percent coarse occur between 5000 and 3800 yrs BP, as well as from 2900 to 500 yrs BP (Fig. 4B,C). The largest peaks in percent coarse (250 μm to 2 mm) in TAH VC4 occur around 4200, 2800, 1900, 1500 and 500 yrs BP and are roughly concurrent, within error of the age model, with similar peaks in TAH VC3. A number of reef block and conglomerate deposits from the Leeward Islands (FP) also occur within a short interval (±100 yrs) of prominent coarse peaks in our longer records (TAH VC3 and VC4, Fig. 4B,C). In particular, two such deposits, dated to ~1900 yrs BP, match well with the largest peaks. Emplacement of large coarse-grained layers is mostly absent in both records over the past 500 yrs and particularly during the period of modern observation. For instance, the peak associated with hurricane Rewa, the largest event during the satellite era (>1970 AD) is considerably smaller (~1.5 percent coarse) than many of the events (>5 percent coarse) during previous active intervals. This indicates that the recent past may be inadequate in assessing possible future tropical cyclone risk in French Polynesia.

4.4. Coral conglomerates, reef blocks and beach ridges

A compilation of coral conglomerate and reef block dates reported in the literature (Table 1) suggests their formation has varied considerably over the past 5000 years. In the Society Islands

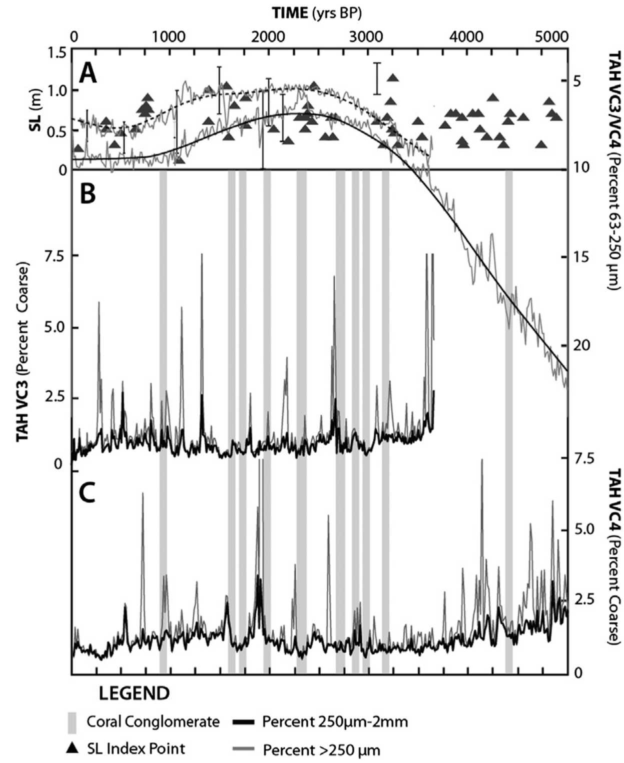

Fig. 4. Comparison of fine sand (63–250 μm) and coarse grain influx (>250 μm and 250 μm to 2 mm fraction) with Holocene sea-level (SL) changes. (A) Fine sand fraction (63–250 μm) for TAH VC3 (dashed) and TAH VC4 (solid). Note *y*-axis is reversed. Black triangles indicate paleo sea-level heights inferred from subaerial corals (Pirazzoli and Montaggioni, 1988) and re-calibrated using Marine09. Coral conglomerate and reef block deposits on Tahaa, Raiatea, Bora Bora, Tupai and Maupiti (Table 1) inferred here to be storm derived are highlighted by vertical bars for comparison to peaks in our overwash records (below). (B) Coarse grained (>250 μm: gray line and 250 μm to 2 mm fraction: black line) deposition in TAH VC3 and (C) TAH VC4.

(Fig. 5B, black line) a large increase in the number of deposits is observed between 3250 and 1500 yrs BP. A similar (3500–1000 yrs BP) increase in event frequency is observed for the entire central South Pacific (Fig. 5B, black dashed line). The broader peak around 3000 yrs BP in this record (as compared to the Society Islands alone) mostly results from events in the Gambier Islands (1500 km SE Tahiti) around this time. In contrast, formation of beach ridges in Northeastern Australia (e.g. (Forsyth et al., 2010, 2012; Nott and Forsyth, 2012)) is highest from 4000 to 3000 yrs BP, 1500 to 1000 yrs BP and 750 yrs BP to present (gray line).

5. Discussion

Derived sedimentary archives demonstrate that deposition of high-energy layers in Tahaa is closely linked with observed tropical cyclone strikes and dated reef block and conglomerate deposits, and are therefore inferred to be storm-induced. Below we provide evidence against alternative mechanisms for changes in grain-size (sea level, tsunamis), and conclude that the two intervals (~5000–3800 and 2900–500 yrs BP) of increased coarse-grained deposition within the lagoon are likely related to higher tropical cyclone activity.

5.1. Confounding effects

Deposition of coarse sand (>250 μm) layers in TAH VC3 and VC4 appears to be relatively unaffected by mid-late Holocene sea level changes in the Pacific (Fig. 4). Identified transitions in coarse

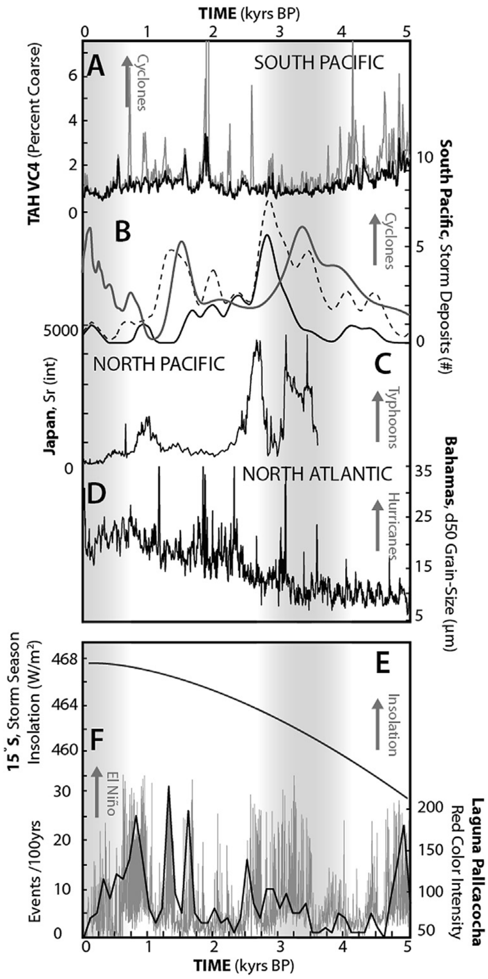

Fig. 5. Comparison of tropical cyclone records from Tahaa, the North Pacific and North Atlantic with records of hypothesized climate forcings. (Top) Tropical cyclone reconstructions from Tahaa (A) Percent >250 µm (gray) and 63–250 µm (black) for TAH VC4 (B) Coral conglomerate and reef blocks (Table 1) from the Society Islands (black line) and the entire Central South Pacific (black dashed line). Record of tropical cyclone deposited beach ridges from Northeastern Australia (compiled in: (Nott and Forsyth, 2012)) – gray line (C) Japan (Woodruff et al., 2009), and (D) Bahamas. (E) Storm season (NDJF) incoming solar insolation at 15° S ((Huybers, 2012), and references therein). (F) Inferred changes in Holocene El Niño frequency based on red-color intensity in sediments from Laguna Pallcacocha, Ecuador (Moy et al., 2002).

material deposition at 5000, 3800, 2900 and 500 yrs BP do not coincide closely with the established 5000–1250 yrs BP age range of the mid-Holocene highstand in French Polynesia ((Grossman et al., 1998) and refs therein). Given the relatively small magnitude (~1–2 m) of sea-level rise over this interval relative to the scale of waves (8–10 m) and storm surge (2–5) noted for storm events (Harmelin-Vivien, 1994), it is unsurprising the mid-Holocene highstand had minimal impact on the sensitivity of our site to tropical cyclone strikes.

In contrast, the deposition of fine sand (250–63 µm) relative to the silt/clay fraction in the lagoon can be closely tied to sea level changes over at least the past 3000 yrs (Fig. 4A). The enrichment in fine sands over the past 1500 yrs likely is induced by lower sea level enhancing the transport of material from the reef flat by shallow water waves, similar to the dynamics noted for tidal flats (Fagherazzi et al., 2006). This effect may also be enhanced by increased advection of silt/clay-sized sediments in the suspended load during periods of higher sea level. Further, the gradual decrease in fine sand accumulation earlier in the record (5000–3000 yrs BP) may occur as the surrounding barrier reef 'catches-up' with sea level, as is noted for reefs around French Polynesia (Montaggioni, 2005). Remnant submerged (~0–10 mbsl) karst topography oceanward of our site indicates reef accretion and erosion has infilled substantial areas of the reef flat since deglacial flooding, possibly syphoning off the source of sand to the lagoon. However, the impact of changes in reef morphology seems restricted to the fine sand fraction as changes in overall sedimentation rate and percent coarse appear largely independent (Fig. 4).

This does not appear to be the case for the coral conglomerates and reef block deposits. Instead, there is a sharp decrease in the number of deposits after 1000 yrs BP (Fig. 5B), coincident with the end of the Mid-Holocene Highstand (Fig. 4). Although our overwash record suggest 1000–500 yrs BP was a period of relatively high storm activity in French Polynesia, conglomerate or reef block deposits from these events may be difficult to identify in the modern surf zone. In contrast, many of barrier reef islands (motu) are constructed from Mid-Holocene Highstand (MHH) coral rubble and relatively speaking, can be readily sampled.

Although tsunamis regularly impact French Polynesia, the geometry of our site, historic records and spatial orientation of coral conglomerate deposits suggest most are storm derived. Our site, being located on the western side of the lagoon separating Tahaa and Raiatea, is sheltered from tsunamis originating from the North, East and South. Only those tsunamis generated along the Tonga trench are likely to significantly impact our study site. A summary of tsunamis known to have hit French Polynesia by Sladen et al. (2007) suggest the Society Islands have not been impacted from the west within the historic interval despite several large earthquakes (>8, Richter Scale) along the Tonga Trench (Okal et al., 2004) and at least one major tsunami over this period. In contrast, most modern storm activity in the central South Pacific occurs to the west of our site (Fig. 1A). Even instrumentally observed tsunamis that have impacted French Polynesia from other orientations have generated relatively small wave heights (<2 m Sladen et al., 2007), likely owing to the steep outer slopes of most barrier-reef fringed islands. This compares with maximum observed storm surge of 4 m and wave heights of up to 12 m during the 1982/1983 tropical cyclone season in French Polynesia alone (Harmelin-Vivien and Laboute, 1986). On longer timescales, the record of coral conglomerate and reef block deposits (Table 1) suggest most of the coarse deposits we observe are likely storm derived. In general, we do not observe synchronous deposition of conglomerates or reef blocks across a large number of islands, all with the same orientation to the sea as would be expected from a large tsunami. Instead, these results are more consistent with storms impacting individual islands at different times from various directions. Although it is not possible to rule out a tsunami origin for any given overwash deposits in our record, on the basis of this analysis and the observed correspondence with known cyclones impacting our site, we interpret most to be storm generated.

5.2. Comparison to other records

Currently, no continuous multi-millennial records of tropical cyclone activity exists for the central South Pacific, however, coral conglomerate, reef block deposits and beach ridges from the region (Fig. 5B) provide key insight into past local and basin-wide tropical cyclone activity. These data indicate that the out-of-phase behavior between tropical cyclone activity in the western and central South Pacific that is seen today (Revell and Goulter, 1986; Hastings, 1990) may have persisted since at least the mid-Holocene. The slight offsets (~300 yrs) between the Central Pacific and Northeastern Australian records may be explained by the methods and substrate dated for each. The beach ridges were dated using OSL (Forsyth et al., 2010, 2012; Nott and Forsyth, 2012) and therefore should give the age of formation. On the other hand, radiocarbon ages of coral conglomerates or reef blocks (Table 1) give the date the coral grew which may predate deposition. At the same time, the residence of old coral material on the barrier is likely limited by reef processes such as bio and wave erosion which work to export it offshore (or into the lagoon) or vertical accretion which would incorporate the material into the reef framework.

A larger coordinated pattern of tropical cyclone activity also emerges between the central South Pacific and other tropical cyclone basins (Fig. 5A–F). A record of landfalling typhoons from two coastal lakes in Kamikoshiki, Japan, indicates the central South Pacific (Tahaa) and North Pacific may be out-of-phase on millennial timescales. This is unexpected given the correlation of modern storm events with periods of El Niño at both sites (e.g. Revell and Goulter, 1986; Wang and Chan, 2002). In contrast, the increased storm activity around French Polynesia between 2900 and 500 yrs BP is more consistent with observations from the Bahamas (Toomey et al., 2013) and Puerto Rico (Donnelly and Woodruff, 2007) over this same interval. A comparison of high-energy event layers in TAH VC3 and VC4 with hydrologic records from Ecuador (Fig. 5F, Moy et al., 2002) and elsewhere in the Pacific (Conroy et al., 2008; Tierney et al., 2012) indicates there may also be a link between ENSO and tropical cyclone activity in the Pacific (Fig. 5A,F). Many of the largest events (2500–1000 yrs BP) in TAH VC4 seem to coincide with periods of decreased runoff in the Eastern Pacific and inferred El Niño frequency (Moy et al., 2002; Conroy et al., 2008). Although the exact evolution of ENSO over the Holocene remains controversial (Cobb et al., 2013), the observed oscillation of storm activity in the central and western South Pacific (Fig. 5B) is suggestive of a regional cyclone dependence on an ENSO-like forcing. However, higher resolution and a wider geographic distribution of both ENSO and tropical cyclone records are needed to statistically test the connection between tropical Pacific dynamics and storm activity across the various basins.

Another explanation for the observed anti-phase behavior between the central South Pacific (active) and North Atlantic (inactive) between 5000 and 3800 yrs BP may be precession driven insolation changes between the hemispheres. Increased cyclone activity prior to 3800 yrs BP in French Polynesia may be related to lower storm season insolation. Work by Korty et al. (2012) suggests precession-related decreases in storm season insolation may have led to a stronger ocean-atmosphere thermal gradient and increased potential intensity in the South Pacific. Precession would be expected to have the opposite effect on storm potential intensity in the North Atlantic.

6. Conclusions

We have reconstructed a 5000-yr record of overwash deposition, likely dominantly by cyclones, from Tahaa, French Polynesia. This record gives us insight into the complex history of cyclone activity in the central South Pacific using new techniques for overwash reconstruction in barrier-reef settings. We find strong coherence between recent coarse-grained deposits and observed events. Coral conglomerate or reef block deposits from Tahaa and nearby islands date closely to several of the older deposits in our records. Together, this suggests high energy event layers deposited in the lagoon are storm derived. In this framework, we can begin to understand long-term patterns in 'storminess' as well as how cyclone activity is influenced by other climate parameters.

Reconstructions from Tahaa highlight a period of higher coarse overwash flux between approximately 2900 and 500 yrs BP, compared with the modern, and an earlier active period occurs between 5000 and 3800 yrs BP. Over the later interval (2900–500 yrs BP), higher than background storm activity is observed near the Bahamas while a general decrease in storm activity near Japan is observed. Central South Pacific and North Atlantic tropical cyclones diverge during the earlier active interval (5000–3800 yrs BP), possibly driven by orbital changes in storm season insolation. These relationships are unexpected given modern observations that indicate tropical cyclone activity in the North Atlantic and central South Pacific increase during opposite ENSO phases. The Tahaa cyclone reconstruction also highlights a period of relative quiescence around French Polynesia today and likewise, the potential risk in the future should levels of activity increase to those observed prior to ~500 yrs BP. Cumulatively, our results reveal the high potential of back-reef settings for recording overwash but also the gaps in our understanding of long-term tropical cyclone patterns.

Acknowledgments

This work was supported through the WHOI Coastal Ocean and Ocean and Climate Change Institutes. We also thank the Sea Education Association and the captain and crew of the SSV Robert C. Seamans. Skye Moret, Michaeline Nelson, Rebecca Sorel, Stephanie Madsen, Phil Lane, Andrea Hawks, Andrew Ashton assisted with field work and laboratory analyses. We also thank an anonymous reviewer for their thoughtful comments.

References

Appleby, P.G., Oldfield, F., 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. CATENA 5, 1–8.
Appleby, P.G., Oldfield, F., 1983. The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103, 29–35.
Basher, R.E., Zheng, X., 1995. Tropical cyclones in the southwest Pacific: spatial patterns and relationships to southern oscillation and sea surface temperature. Journal of Climate 8, 1249–1260.
Blumenstock, D.I., Fosberg, F., Johnson, C.G., 1961. The re-survey of typhoon effects on Jaluit Atoll in the Marshall Islands. Nature 189, 618–620.
Blumenstock, D.I., 1958. Typhoon effects at Jaluit atoll in the Marshall Islands. Nature 182, 1267–1269.
Chevalier, J., Salvat, B., 1976. Etude geomorphologique de l'atoll ferme de Taiaro. In: Cah Pac., vol. 19, pp. 169–201.
Clement, A.C., Seager, R., Cane, M.A., 2000. Suppression of El Niño during the mid-Holocene by changes in the Earth's Orbit. Paleoceanography 15, 731–737.
Cobb, K.M., Westphal, N., Sayani, H.R., Watson, J.T., Di Lorenzo, E., Cheng, H., Edwards, R., Charles, C.D., 2013. Highly variable El Niño–Southern Oscillation throughout the Holocene. Science 339, 67–70.
Conroy, J.L., Overpeck, J.T., Cole, J.E., Shanahan, T.M., Steinitz-Kannan, M., 2008. Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. Quaternary Science Reviews 27, 1166–1180.
Curray, J.R., Shepard, F.P., Veeh, H.H., 1970. Late Quaternary sea-level studies in Micronesia: CARMARSEL Expedition. Geological Society of America Bulletin 81, 1865–1880.
Delibrias, G., Guillier, M.T., Labeyrie, J., 1969. Gif natural radiocarbon measurements III. Radiocarbon 11 (2), 327–344.
Donnelly, J.P., Woodruff, J.D., 2007. Intense hurricane activity over the past 5,000 years controlled by El Nino and the West African monsoon. Nature 447, 465–468.
Donnelly, J.P., Roll, S., Wengren, M., Butler, J., Lederer, R., Webb, T., 2001. Sedimentary evidence of intense hurricane strikes from New Jersey. Geology 29, 615–618.
Fagherazzi, S., Carniello, L., D'Alpaos, L., Defina, A., 2006. Critical bifurcation of shallow microtidal landforms in tidal flats and salt marshes. Proceedings of the National Academy of Sciences 103, 8337–8341.
Forsyth, A.J., Nott, J., Bateman, M.D., 2010. Beach ridge plain evidence of a variable late-Holocene tropical cyclone climate, North Queensland, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 297, 707–716.
Forsyth, A.J., Nott, J., Bateman, M.D., Beaman, R.J., 2012. Juxtaposed beach ridges and foredunes within a ridge plain-Wonga Beach, northeast Australia. Marine Geology 307–310, 111–116.
Gischler, E., 2011. Sedimentary facies of Bora Bora, Darwin's type barrier reef (Society Islands, south Pacific): the unexpected occurrence of non-skeletal grains. Journal of Sedimentary Research 81, 1–17.
Gleason, M., 1993. Effects of disturbance on coral communities: bleaching in Moorea, French Polynesia. Coral Reefs 12, 193–201.
Glynn, P.W., 1984. Widespread coral mortality and the 1982–83 El Nino warming event. Environmental Conservation 11, 133–146.
Grossman, E., Fletcher III, C., Richmond, B., 1998. The Holocene sea-level highstand in the equatorial Pacific: analysis of the insular paleosea-level database. Coral Reefs 17, 309–327.

Guilcher, A., 1969. Les Récifs et lagons coralliens de Mopelia et de Bora-Bora (îles de la Société): et quelques autres récifs et lagons de comparaison (Tahiti, Scilly, Tuamotu occidentales); morphologie, sédimentologie, fonctionnement hydrologique, vol. 38. IRD Editions.
Guillou, H., Maury, R.C., Blais, S., Cotten, J., Legendre, C., Guille, G., Caroff, M., 2005. Age progression along the Society hotspot chain (French Polynesia) based on new unspiked K-Ar ages. Bulletin de la Societe Géologique de France 176, 135–150.
Harmelin-Vivien, M.L., Laboute, P., 1986. Catastrophic impact of hurricanes on atoll outer reef slopes in the Tuamotu (French Polynesia). Coral Reefs 5, 55–62.
Harmelin-Vivien, M.L., 1994. The effects of storms and cyclones on coral reefs: a review. Journal of Coastal Research, 211–231.
Harris, P., Fichez, R., Fernandez, J.-M., Golterman, H., Badie, C., 2001. Using geochronology to reconstruct the evolution of particulate phosphorus inputs during the past century in the Papeete Lagoon (French Polynesia). Oceanologica Acta 24, 1–10.
Hastings, P.A., 1990. Southern oscillation influences on tropical cyclone activity in the Australian/south-west Pacific region. International Journal of Climatology 10, 291–298.
Hubbs, C.L., Bien, G.S., 2006. La Jolla natural radiocarbon measurements V.
Huybers, P., 2012. inso.m. http://www.people.fas.harvard.edu/~phuybers/Mfiles/Toolbox/.
Kench, P.S., Brander, R.W., 2006. Wave processes on coral reef flats: implications for reef geomorphology using Australian case studies. Journal of Coastal Research, 209–223.
Knapp, K.R., Kruk, M.C., Levinson, D.H., Diamond, H.J., Neumann, C.J., 2010. The International Best Track Archive for Climate Stewardship (IBTrACS). Bulletin of the American Meteorological Society 91, 363–376.
Korty, R.L., Camargo, S.J., Galewsky, J., 2012. Variations in tropical cyclone genesis factors in simulations of the Holocene epoch. Journal of Climate 25, 8196–8211.
Lane, P., Donnelly, J.P., Woodruff, J.D., Hawkes, A.D., 2011. A decadally-resolved paleohurricane record archived in the late Holocene sediments of a Florida sinkhole. Marine Geology 287, 14–30.
Liu, K.-b., Fearn, M.L., 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. Geology 21, 793–796.
McKee, E.D., 1959. Storm sediments on a Pacific atoll. Journal of Sedimentary Research 29.
Montaggioni, L., Pirazzoli, P., 1984. The significance of exposed coral conglomerates from French Polynesia (Pacific Ocean) as indicators of recent relative sea-level changes. Coral Reefs 3 (1), 29–42.
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.
Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M., 2002. Variability of El Nino/Southern Oscillation activity at millennial timescales during the Holocene epoch. Nature 420, 162–165.
Nott, J., Forsyth, A., 2012. Punctuated global tropical cyclone activity over the past 5,000 years. Geophysical Research Letters 39, L14703.
Okal, E.A., Borrero, J., Synolakis, C.E., 2004. The earthquake and tsunami of 1865 November 17: evidence for far-field tsunami hazard from Tonga. Geophysical Journal International 157, 164–174.
Pirazzoli, P.A., Montaggioni, L.F., 1986. Late Holocene sea-level changes in the northwest Tuamotu Islands, French Polynesia. Quaternary Research 25 (3), 350–368.
Pirazzoli, P., Montaggioni, L., 1987. Les îles Gambier et l'atoll de Temöe (Polynésie française): anciennes lignes de rivage et comportement géodynamique. Géodynamique 2 (1), 13–25.
Pirazzoli, P., Montaggioni, L., 1988. Holocene sea-level changes in French Polynesia. Palaeogeography, Palaeoclimatology, Palaeoecology 68 (2), 153–175.
Pirazzoli, P.A., et al., 1987. Late Holocene sea levels and coral reef development in Vahitahi Atoll, eastern Tuamotu Islands, Pacific Ocean. Marine Geology 76 (0), 105–116.
Pirazzoli, P., et al., 1988. Late Holocene sea level indicators from twelve atolls in the central and eastern Tuamotus (Pacific Ocean). Coral Reefs 7 (2), 57–68.
Pirazzoli, P., 1985a. Sea-level changes in Rangiroa. In: Ricard, M. (Ed.), Rangiroa Atoll. Fifth International Coral Reef Congress, pp. 192–198.
Pirazzoli, P., 1985b. Leeward islands, Maupiti, Tupai, Bora Bora, Huahine, Society archipelago: 5th International Coral Reef Symposium, Tahiti. In: Proceedings.
Pirazzoli, P.A., 1987. A reconnaissance and geomorphological survey of Temoe atoll, Gambier Islands (South Pacific). Journal of Coastal Research, 307–323.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Burr, G.S., Edwards, R.L., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP.
Revell, C.G., Goulter, S.W., 1986. South Pacific tropical cyclones and the Southern Oscillation. Monthly Weather Review 114, 1138–1145.
Scileppi, E., Donnelly, J.P., 2007. Sedimentary Evidence of Hurricane Strikes in Western Long Island vol. 8. Geochem. Geophys. Geosyst, New York, p. Q06011.
Sladen, A., Hébert, H., Schindelé, F., Reymond, D., 2007. Evaluation of far-field tsunami hazard in French Polynesia based on historical data and numerical simulations. Natural Hazards and Earth System Science 7, 195–206.
Teissier, R., 1982. Les Cyclones en Polynésie Française: 1878, 1903, 1905, 1906. Société des études océaniennes.
Tierney, J., Oppo, D., LeGrande, A., Huang, Y., Rosenthal, Y., Linsley, B., 2012. The influence of Indian Ocean atmospheric circulation on Warm Pool hydroclimate during the Holocene Epoch. Journal of Geophysical Research 117.
Toomey, M.R., Curry, W.B., Donnelly, J.P., Hengstum, P.J., 2013. Reconstructing 7000 years of North Atlantic hurricane variability using deep-sea sediment cores from the western Great Bahama Bank. Paleoceanography 28 (1), 31–41.
von Reden, K.F., Roberts, M.L., Burton, J.R., Beaupre, S.R., 2012. Optimizing a microwave gas ion source for continuous-flow accelerator mass spectrometry. Review of Scientific Instruments 83, 02B304-304.
Wang, B., Chan, J.C.L., 2002. How strong ENSO events affect tropical storm activity over the western North Pacific*. Journal of Climate 15, 1643–1658.
Woodroffe, C., et al., 1990. Holocene emergence in the Cook islands, South Pacific. Coral Reefs 9 (1), 31–39.
Woodruff, J.D., Donnelly, J.P., Okusu, A., 2009. Exploring typhoon variability over the mid-to-late Holocene: evidence of extreme coastal flooding from Kamikoshiki, Japan. Quaternary Science Reviews 28, 1774–1785.