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High-precision U-series dating of very young cyclone-transported coral reef blocks from Heron and Wistari reefs, southern Great Barrier Reef, Australia

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Abstract

Numerous high-energy-transported coral reef blocks occur on the outer reef flats of Heron and Wistari reefs at the southern end of the Great Barrier Reef. In a pilot study, five samples from Heron and one from Wistari were collected for high-precision U-series dating by thermal ionization mass spectrometry. Five of the six dated corals yield U-series dates that suggest these corals were killed and transported during the last century. Without precise knowledge of cyclone impacts in the area, it is not possible to unequivocally link these reef blocks to specific cyclones. Nevertheless, this pilot study demonstrates that cyclone-transported coral reef blocks over the past 300 years can be precisely dated to an age uncertainty of ±1–4 years. This opens up the opportunity for high-age-resolution reconstruction of cyclone history and high-precision assessment of the trend and frequency of cyclone occurrences over the past millennium, as well as for a better understanding of anthropogenic impact on cyclone activity.

1. Introduction

Tropical cyclones have a severe impact on human populations and economy and play an important role in coral reef development and biodiversity (Connell et al., 1997; Hughes and Connell, 1999). Cyclones are predicted to generally increase in magnitude and frequency under scenarios of future climate change (Henderson-Sellers et al., 1998; Walsh and Ryan, 2000; Goldenberg et al., 2001; IPCC, 2007), despite some spatial variations, e.g. lower Atlantic hurricanes during the 1970–1980s (Landsea et al., 1996; Easterling et al., 2000; Webster et al., 2005; Nyberg et al., 2007). However, assessing anthropogenic effects on variations of cyclones (especially since the Industrial Revolution) requires decoupling recent and future trends from longer-term periodicities, as well as a better knowledge of cyclone occurrences over the past few hundred years. Australia has a vast coastline, much of which is vulnerable to cyclone impact. However, historic records are limited to only the last 150 years of European settlement in tropical areas of Australia. Holocene records of tropical cyclone frequency have been obtained for some areas of the Great Barrier Reef (Hayne and Chappell, 2001; Nott and Hayne, 2001); yet, the records are limited and the resolution is low.

The frequency and magnitude of cyclones can be recorded in various archives, such as transported boulders, storm ridges/ramparts, lagoon and coastal sediments (sediment structure and grain-size distribution), near-shore lakes, sinkholes or swamps (fingerprints of sea-water surges), and even tree-rings (Nott, 1997; Hayne and Chappell, 2001; Nott and Hayne, 2001; Yu et al., 2004, 2006b; Miller et al., 2006). Through dating and characterising such geological archives, cyclone histories can be reconstructed. In a previous study, we showed a correlation between the ages of coral boulders on Yongshu reef in the South China Sea and both increased lagoon deposition rates (Yu et al., 2006b) and coarse-grained sediment content peaks (Yu et al., 2008) and interpreted this result

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as a record of the number of cyclone/tsunami events over the past millennium (Yu et al., 2004, 2006b, 2008). In this study, we report new data from high-precision U-series dating of cyclone-transported coral reef blocks on the reef flats of Heron and Wistari reefs at the southern end of the Great Barrier Reef. The results show that transport of coral reef blocks by high-energy events occurred during the last 300 years and these blocks can be dated with an age uncertainty of $\pm$1–4 years. We use this level of precision as a basis to discuss the relationship between the dated events and historic cyclone records and to investigate the potential for high-resolution systematic reconstruction of cyclone history over the last millennium.

2. Site description

Heron (23°32′46″S, 151°57′20″E) and Wistari (23°28′14″S, 151°53′20″E) reefs are both off-shore lagoonal platform reefs in the Capricorn Group at the southern end of the Great Barrier Reef, about 150 km E of Rockhampton or 80 km northeast of Gladstone (Fig. 1).

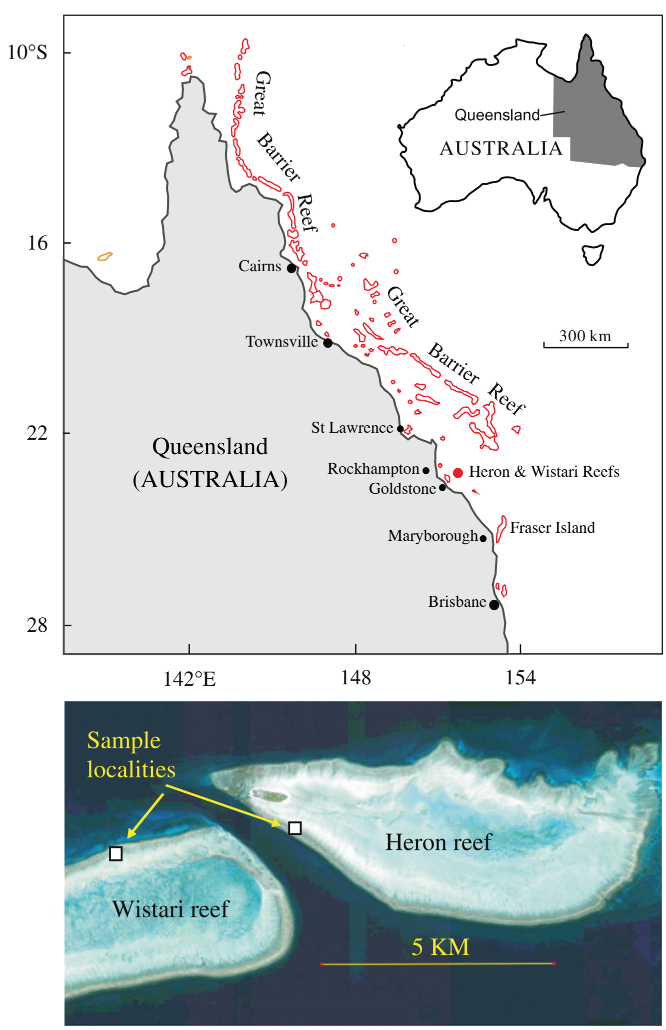

Fig. 1. Map showing the location of Heron and Wistari reefs with respect to the Great Barrier Reef and coastal Queensland.

Both reefs are elongate reef systems developed on a Pleistocene basement (Davies, 1974; Marshall, 1983), separated by a narrow (width <1 km) northwest-trending channel. They have well-developed windward rims to the south, and less well-developed leeward rims to the north. Both reefs show concentric zoning in reef morphology and depositional environment, with well-developed lagoons in the centre. Detailed coring, seismic profiling and radiocarbon dating of the Heron reef lagoon (Smith et al., 1998) indicate that lagoon sedimentation started at least 4200 years BP (uncorrected radiocarbon dates), with the windward margin reaching sea level around 2700 years BP. Both reefs are frequently affected by tropical cyclones. Meteorological and historic records show that, during the last century, a total of 145 cyclones were documented to have hit the Queensland coastline between 1901 and 2000 AD (see http://www.windworker.com.au/qldcyclones.htm), with 25 of them crossing the coast between St Lawrence (~270 km northwest of Heron and Wistari reefs) and Maryborough (~240 m southwest of Heron and Wistari reefs).

3. Sample collection, analytical methods and results

Numerous transported reef blocks (probably in thousands, some a few meters across) occur on the reef flats of Heron and Wistari reefs (Fig. 2). During a brief fieldtrip by one of us (DN), a number of surface samples were collected from reef blocks on both reefs using a geological hammer. Six samples, including five from southeast Heron reef and one from northeast Wistari reef (Fig. 1), were chosen for high-precision U-series dating by thermal ionization mass spectrometry (TIMS) at the University of Queensland. Samples from coral colonies showing fresh surfaces were taken 15–60 mm below the surfaces of the colonies. Detailed analytical procedures are described in Zhao et al. (2001) and Yu et al. (2006a). Our samples were

Fig. 2. Examples of cyclone-transported coral reef blocks on the reef flat at Heron Island.

Table 1
U-series isotope data and ages for transported coral reef blocks on Heron and Wistari reefs

Sample name	Distance to surface (mm)	U ($\times 10^{-6}$ g/g)	^{232}Th ($\times 10^{-9}$ g/g)	^{230}Th ($\times 10^{-15}$ g/g)	(^{230}Th/^{232}Th)	(^{230}Th/^{238}U)	(^{234}U/^{238}U)	Uncorr. ^{230}Th age (years)	Corr. ^{230}Th age I (years)	Corr. ^{230}Th age II (years)	Initial δ^{234}U	Surface or mortality age (AD)
HR-1	15	2.526	0.035	16.0	85.7	0.000391±39	1.1447±13	37.1±3.7	36.8±3.7	36.3±3.7	144.7±1.3	1970±4
HR-2	50	2.988	0.152	52.9	65.2	0.001095±14	1.1436±17	104.1±1.3	102.8±1.5	100.9±2.1	143.6±1.7	1907±3
HR-3	25	2.929	0.106	32.1	56.8	0.000678±10	1.1459±13	64.4±0.9	63.4±1.1	62.1±1.5	146.0±1.3	1944±2
HR-4	30	2.667	0.039	42.8	205.3	0.000991±34	1.1471±15	94.0±3.2	93.6±3.2	93.1±3.2	147.2±1.5	1914±4
HR-5	60	2.732	0.068	128.8	353.8	0.002912±38	1.1475±16	276.3±3.6	275.6±3.6	274.7±3.7	147.7±1.6	1734±5
WRW-3	30	4.090	0.029	45.0	292.4	0.000680±34	1.1419±20	64.7±3.3	64.6±3.3	64.3±3.3	141.9±2.0	1943±4

Note: HR and WTW refer to samples from Heron reef and western Wistari reef. Sample HR-1 is *Goniostrea* sp., samples HR-2 to -5 are *Platygra* sp., and sample WTW-3 is *Porites* sp. Ratios in parentheses are activity ratios calculated from the atomic ratios, using decay constants of Cheng et al. (2000). Errors are at 2σ level (error figures for the isotopic ratios refer to the last two significant digits). $\delta^{234}U = [(^{234}U/^{238}U)-1]\times 1000$ and $\delta^{234}U(T) = \delta^{234}U(O)e^{\lambda 234T}$, where the age ($T$) is calculated using Isoplot EX 2.3 (Ludwig, 1999). 2σ errors in the uncorrected (uncorr.) ages were propagated directly from the uncertainties in (^{230}Th/^{238}U) and (^{234}U/^{238}U). The corrected (corr.) ^{230}Th age I was calculated using non-radiogenic (^{230}Th/^{232}Th) = 1.0±0.5, whereas the corr. ^{230}Th age II, using non-radiogenic (^{230}Th/^{232}Th) = 2.0±1.0. The TIMS U-series ages are relative to the year dated. The surface or mortality age (in years AD) refers to the time when the coral head died, which was estimated based on the corrected TIMS ^{230}Th age I and the number of annual layers above the sampling location (assuming a growth rate of 10–20 mm/year with a mean of 15±5 mm/year). The 2δ uncertainties in the mortality ages also include errors in the growth rate estimation.

measured in two separate sets, with HR-1, HR-4 and WRW-3 preceding measurement of the other three samples. In the first set, without suspecting the samples were so young, only ~400 mg material per sample was processed following standard procedures. In the second set, about 1 g material was used and extra precaution, including the use of longer preheating procedures and measurement time, was taken in the TIMS measurement of Th isotope ratios. As a result, about 3–10% (at 2σ level) errors were obtained for uncorrected ^{230}Th ages of the first set of samples, whereas for the second set much better age precisions were achieved (1.3–1.5%) (Table 1). The results indicate the near surface ages of these reef blocks ranged from 37±4 to 276±4 years. Assuming a coral colony growth rate of 15 mm/year and that post-mortality erosion was minimal, we calculated the surface (or mortality) ages of the reef blocks and used this as the age of mortality (see Section 4.2).

4. Discussion

4.1. Reliability of the ^{230}Th ages

Dating coral samples of less than 500 years is challenging due to a number of factors. First, the extremely low radiogenic ^{230}Th in the samples is difficult to measure precisely, and procedural blanks and errors in spike calibration have a greater influence on age precision than for older samples. Yu et al. (2006a) and Zhao et al. (2008) made a detailed assessment of these analytical factors. The testing results show that the total amount of procedural blanks in our laboratory is $3.3\pm3.3\times10^{-17}$ g (or 0.033±0.033 fg), contributing less than 0.1 year to the age calculation for corals with 2–3 ppm U. This level of blank is negligible considering the fact that the six dated samples contain 16–129 fg ^{230}Th. Our blanks from loading samples onto zone-refined rhenium filament ribbons (incorporating impurities from colloidal graphite, rhenium ribbon and loading acid) are negligible, as they display no discernible signals on masses 229, 230, 233, 234 and 236. The total procedural blanks were mainly derived from the sample preparation process (including sample dissolution, Fe co-precipitation and column chemistry).

The second factor that affects the precision and reliability of the ages is the amount and isotopic composition of non-radiogenic Th components in the samples (Cobb et al., 2003; Yu et al., 2006a). This is also discussed in detail by Yu et al. (2006a), who considered that aeolian continental dusts would be the predominant source of non-radiogenic Th in the South China Sea. They also used live corals of known ages to back-calculate non-radiogenic ^{230}Th/^{232}Th activity ratios in these samples, which is ~1.3. As Heron and Wistari reefs are only 70 km from the coast, much closer than the distance between Yongshu reef and the closest landmass, we consider that aeolian continental dusts would also be a primary source of non-radiogenic Th in our samples. In addition, using a Great Barrier Reef coral core of known age from the AIMS core library, we determined a non-radiogenic $^{230}Th/^{232}Th$ activity ratio of ~1, which is expected for aeolian continental dusts. In other words, assuming non-radiogenic $^{230}Th/^{232}Th$ activity ratio of ~1, the corrected ^{230}Th ages agree well with independent layer-counting ages (Yu and Lawrence, unpublished data). Thus we use non-radiogenic $^{230}Th/^{232}Th = 1$ to calculate the corrected ^{230}Th ages, which show almost no difference from the uncorrected ^{230}Th ages. The much smaller influence of non-radiogenic Th components on our samples, as compared to samples from Yongshu reef, is due to the fact that the level of ^{232}Th (reflecting the level of non-radiogenic ^{230}Th) is an order of magnitude lower. Because of this, the influence from the uncertainty in the non-radiogenic $^{230}Th/^{232}Th$ ratio assumption is minimal. For instance, even if we assume a non-radiogenic $^{230}Th/^{232}Th$ activity ratio of ~2, the corresponding corrected ^{230}Th ages will be only 0.4–3.2 years younger than the uncorrected ^{230}Th ages (see Table 1). Hence, we consider that the influence of non-radiogenic Th components in our samples is negligible.

The third factor that affects the reliability of the ages is whether the samples have experienced secondary alteration and U mobility. Except for WRW-3, U contents in all other samples range from 2.5 to 3.0 ppm U and initial $\delta^{234}U$ from 144 ± 2‰ to 148 ± 2‰, within the normal ranges (e.g. 2.5–3.5 ppm, 146 ± 3‰) for modern pristine corals and seawater (Stirling et al., 1998; Henderson, 2002; Yu et al., 2006a; Scholz and Mangini, 2007). U in WRW-3 (~4.1 ppm) is marginally higher than the normal range of 2.5–3.5 ppm, suggesting that its age might be susceptible to some secondary disturbance (minor U gain). To what degree this will impact the age is unclear, although it was noted that post-depositional U gain usually results in ^{230}Th ages that are apparently too young (Lazar et al., 2004; Scholz and Mangini, 2007).

4.2. Assumptions and implications of the coral ages

To what degree our coral ages precisely record the timing of cyclone events is dependent upon two main factors. First, were the dated corals alive when they were transported by the cyclones? Second, was there any erosion after the reef blocks were transported onto the reef flat? Violation of one or both of these assumptions would provide ages that were older than the date of cyclone transport. It has been shown in a number of studies that loosely attached living coral colonies are commonly dislodged and transported from where they lived underwater to reef flats above sea level by cyclones and other high-energy wave events (Done, 1992; Massel and Done, 1993; Gilmour and Smith, 2006). Many other studies show that live coral cover may be significantly reduced after major cyclone or tsunami events, suggesting live corals are vulnerable to destruction and dislodgement by extreme wave events (Cheal et al., 2002; Kumaraguru et al., 2005; Wantiez et al., 2006; Done et al., 2007). On Heron and Wistari reefs, the reef fronts are dominated by live corals, and so the probability for live corals to be transported by cyclone events is high. We attempted to date the freshest material we found on the transported reef blocks so as to increase the probability of dating the youngest part of the reef block. Nevertheless, we acknowledge that our ages are maximum age estimates for the date of inferred cyclone occurrence, and realize that the real cyclone age associated with each block might have been later than our age dates.

The second question regarding post-mortality erosion is even more difficult to assess. In the study of coral blocks and storm history on Yongshu reef in the South China Sea, Yu et al. (2004, 2006b, 2008) showed that the surface ages of the transported reef blocks correlate in timing with peaks of coarse-grained sediment that were independently dated using incorporated branching coral fragments. This excellent age correlation implies the erosion rate of transported reef blocks was probably negligible, which is also supported by field evidence such that none of the transported blocks show any signs of younger coral overgrowth, encrustation or subtidal alteration. Considering the fact that some of the dated blocks from Yongshu were up to 1000 years older (much older than dated corals in this study) and yet they show no evidence of erosion, it is possible that the much younger coral blocks from Heron and Wistari reefs experienced little erosion over the last century. Based on previous direct measurements of limestone erosion rates across a variety of climatic conditions in Australia (Stone et al., 1994; Smith et al., 1995) (ranging from 0.005 mm/year in arid zones to 0.2 mm/year in equatorial environment), we estimate that the loss of reef blocks to erosion on Heron and Wistari Reefs over 100 years should be less than 20 mm, or about 1 year of coral growth or less. In reality, erosion rates should be at least one or two orders of magnitude lower than 20 mm/century, otherwise ~24 m of coral profile would have been eroded on a last-interglacial reef terrace, which is clearly unrealistic. Nevertheless, if erosion did occur, the surface ages of the dated coral blocks should be considered as the maximum ages of the corresponding cyclone events.

4.3. Comparison with historic records of cyclone events

As described previously, meteorological and historic records (see http://www.windworker.com.au/qldcyclones.htm) show a total of 145 cyclones hit the Queensland coastline between 1901 and 2000 AD, with 25 crossing the coast between St. Lawrence to the north (~270 km northwest of Heron and Wistari reefs) and Maryborough to the south (~240 m southwest of Heron and Wistari reefs), although cyclone records for the earlier part of the century may not be complete (especially during the two World Wars). When plotting the surface (or mortality) ages of our dated samples on the histograms of the 25 cyclone records in the vicinity (Fig. 3), it appears that these reef block ages do fall within the frequency distribution of these cyclones. In addition, we also outlined potential cyclones in

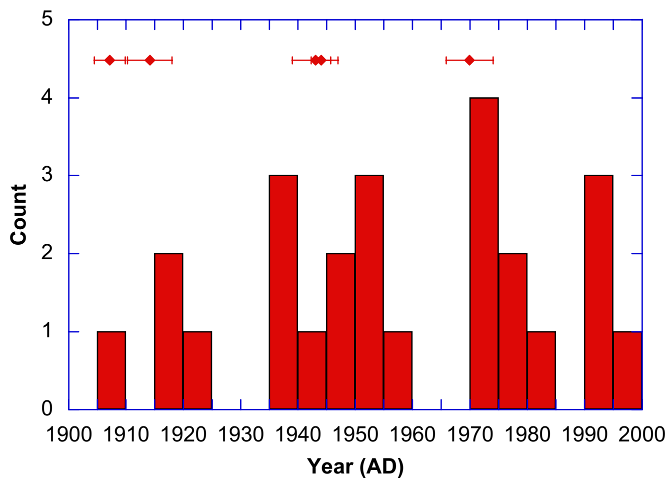

Fig. 3. Histograms of cyclones crossing the coastal area from St. Lawrence to Maryborough (see Fig. 1) between 1901 and 2000 AD. Also shown for comparison are surface (mortality) ages of the dated coral reef blocks.

Table 2
Transported reef blocks and potential cyclones that might be responsible

Sample name	Surface or mortality age (AD)	Potentially responsible cyclones
HR-1	1970 ± 4	Cyclone Emily on 2 April 1972 crossed south of Gladstone (~80 km southwest of Heron reef) and created huge waves claiming 8 lives.
HR-2	1907 ± 3	The cyclone on 12 March 1908 caused widespread damage to buildings, trees, fences and telegraph lines near St. Lawrence (~270 km northeast of Heron reef).
HR-3 WRW-3	1944 ± 2 1943 ± 4	The cyclone on 2 February 1942 crossed north Rockhampton (~150 km west of Heron reef). Other potential cyclones include one passing east of Fraser Island (~200 km southeast of Heron reef) on 4 April 1946 causing flooding and one crossing at Broadsound (~380 km northwest of Heron reef) on 10 February 1947 causing damage to infrastructure and loss of life.
HR-4	1914 ± 4	Four major cyclones occurred within 450 km radius between 1915 and 1919. The cyclone on 27 December 1916 caused severe damage on Whitsunday Island (~410 km northwest of Heron reef), flooding at Clermont (~450 km northwest of Heron reef), and claimed 62 lives. The cyclone on 21 January 1918 created huge flooding at Rockhampton (~150 km west of Heron reef) and claimed 30 lives. The cyclone cross Maryborough (~240 km south of Heron reef) resulted in serious washout.

the vicinity of Heron and Wistari reefs that might be responsible for the transport of the dated reef blocks in this study (Table 2). However, without precise knowledge on which cyclones have physically crossed Heron and Wistari reefs, it is impossible to match coral mortality ages with individual cyclones. Overall, our results do demonstrate the potential to use reef block ages to reconstruct cyclone events and their frequencies over the past few hundred years, provided a large number of reef blocks are dated to produce a statistically significant age population. As several thousand transported reef blocks are present on the reef flats, such a study is indeed feasible. In addition, if the sizes and elevations of the coral reef blocks and their distances to the reef fronts are precisely determined, it is also possible to calculate the energy of the cyclone-induced waves and thus the intensity of the cyclones (Nott, 2003). More detailed study of these aspects is under way.

5. Conclusions

In this pilot study, we demonstrate that coral reef blocks on the reef flats of Heron and Wistari reefs at the southern end of the Great Barrier Reef were transported by high-energy events during the past 300 years and can be precisely dated to an age uncertainty of ±1–4 years. Five of the six dated corals yield U-series dates that indicate that these corals were killed and transported over the last century. However, without precise knowledge about cyclone intensity and tracks in relation to Heron and Wistari reefs, it is not possible to unequivocally link these coral reef blocks to individual cyclones. Nevertheless, this pilot study shows the potential for cyclone history over the past few hundred years to be reconstructed with unprecedented age precision and detail using transported coral reef blocks, probably in combination with chronology and characterisation of other associated geological archives, such as storm ridges and lagoon sediments. Such study may augment historic records of cyclones back to the past millennium, enabling us to assess the trend and frequency of cyclone occurrences over the past few hundred years.

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References

Cheal, A.J., Coleman, G., Delean, S., Miller, I., Osborne, K., Sweatman, H., 2002. Responses of coral and fish assemblages to a severe but short-lived tropical cyclone on the Great Barrier Reef, Australia. Coral Reefs 21, 131–142.

Cheng, H., Edwards, R.L., Hoff, J., Gallup, C.D., Richards, D.A., Asmerom, Y., 2000. The half-lives of uranium-234 and thorium-230. Chemical Geology 169, 17–33.

Cobb, K.M., Charles, C.D., Cheng, H., Kastner, M., Edwards, R.L., 2003. U/Th-dating living and young fossil corals from the Central Tropical Pacific. Earth and Planetary Science Letters 210, 91–103.

Connell, J.H., Hughes, T.P., Wallace, C.C., 1997. A 30-year study of coral abundance, recruitment, and disturbance at several scales in space and time. Ecological Monographs 67, 461–488.

Davies, P.J., 1974. Subsurface solution unconformities at Heron Island, Great Barrier Reef. In: Proceedings of the Second International Coral Reef Symposium, Brisbane, Queensland, pp. 573–578.

Done, T.J., 1992. Effects of tropical cyclone waves on ecological and geomorphological structures on the Great-Barrier-Reef. Continental Shelf Research 12, 859–872.

Done, T., Turak, E., Wakeford, M., DeVantier, L., McDonald, A., Fisk, D., 2007. Decadal changes in turbid-water coral communities at Pandora Reef: loss of resilience or too soon to tell? Coral Reefs 26, 789–805.

Easterling, D.R., Evans, J.L., Groisman, P.Y., Karl, T.R., Kunkel, K.E., Ambenje, P., 2000. Observed variability and trends in extreme climate events: a brief review. Bulletin of the American Meteorological Society 81, 417–425.

Gilmour, J.P., Smith, L.D., 2006. Category 5 cyclone at Scott Reef, northwestern Australia. Coral Reefs 25, 200.

Goldenberg, S.B., Landsea, C.W., Mestas-Nunez, A.M., Gray, W.M., 2001. The recent increase in Atlantic hurricane activity: causes and implications. Science 293, 474–479.

Hayne, M., Chappell, J., 2001. Cyclone frequency during the last 5000 years at Curacoa Island, north Queensland, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 168, 207–219.

Henderson, G.M., 2002. Seawater (U-234/U-238) during the last 800 thousand years. Earth and Planetary Science Letters 199, 97–110.

Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.L., Webster, P., McGuffie, K., 1998. Tropical cyclones and global climate change: a post-IPCC assessment. Bulletin of the American Meteorological Society 79, 19–38.

Hughes, T.P., Connell, J.H., 1999. Multiple stressors on coral reefs: a long-term perspective. Limnology and Oceanography 44, 932–940.

Intergovernmental Panel on Climate Change (IPCC), 2007. Summary for policymakers of the synthesis report of the IPCC fourth assessment report, 〈http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf〉.

Kumaraguru, A.K., Jayakumar, K., Wilson, J.J., Ramakritinan, C.M., 2005. Impact of the tsunami of 26 December 2004 on the coral reef environment of Gulf of Mannar and Palk Bay in the southeast coast of India. Current Science 89, 1729–1741.

Landsea, C.W., Nicholls, N., Gray, W.M., Avila, L.A., 1996. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. Geophysical Research Letters 23, 1697–1700.

Lazar, B., Enmar, R., Schossberger, M., Bar-Matthews, M., Halicz, L., Stein, M., 2004. Diagenetic effects on the distribution of uranium in live and Holocene corals from the Gulf of Aqaba. Geochimica et Cosmochimica Acta 68, 4583–4593.

Ludwig, K.R., 1999. Users Manual for Isoplot/Ex version 2, A Geochronological Toolkit for Microsoft Excel, vol. 1. Berkeley Geochronology Center Special Publications, p. 44.

Marshall, J.F., 1983. Lithology and diagenesis of the carbonate foundations of modern reefs in the southern GBR. BMR Journal of Australian Geology and Geophysics 8, 253–265.

Massel, S.R., Done, T.J., 1993. Effects of cyclone waves on massive coral assemblages on the Great-Barrier-Reef-meteorology, hydrodynamics and demography. Coral Reefs 12, 153–166.

Miller, D.L., Mora, C.I., Grissino-Mayer, H.D., Mock, C.J., Uhle, M.E., Sharp, Z., 2006. Tree-ring isotope records of tropical cyclone activity. Proceedings of the National Academy of Sciences of the United States of America 103, 14294–14297.

Nott, J., 1997. Extremely high-energy wave deposits inside the Great Barrier Reef, Australia: determining the cause—tsunami or tropical cyclone. Marine Geology 141, 193–207.

Nott, J., 2003. Waves, coastal boulder deposits and the importance of the pre-transport setting. Earth and Planetary Science Letters 210, 269–276.

Nott, J., Hayne, M., 2001. High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5000 years. Nature 413, 508–512.

Nyberg, J., Malmgren, B.A., Winter, A., Jury, M.R., Kilbourne, K.H., Quinn, T.M., 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. Nature 447, 698-U11.

Scholz, D., Mangini, A., 2007. How precise are U-series coral ages? Geochimica et Cosmochimica Acta 71, 1935–1948.

Smith, D.I., Greenaway, M.A., Moses, C., Spate, A.P., 1995. Limestone weathering in eastern Australia. 1. Erosion rates. Earth Surface Processes and Landforms 20, 451–463.

Smith, B.T., Frankel, E., Jell, J.S., 1998. Lagoonal sedimentation and reef development on Heron Reef, southern Great Barrier Reef province. Special Publication of the International Association of Sedimentologists 25, 281–294.

Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., 1998. Timing and duration of the last interglacial: evidence for a restricted interval of widespread coral reef growth. Earth and Planetary Science Letters 160, 745–762.

Stone, J., Allan, G.L., Fifield, L.K., Evans, J.M., Chivas, A.R., 1994. Limestone erosion measurements with cosmogenic Cl-36 in calcite—preliminary-results from Australia. Nuclear Instruments & Methods in Physics Section B 92, 311–316.

Walsh, K.J.E., Ryan, B.F., 2000. Tropical cyclone intensity increase near Australia as a result of climate change. Journal of Climate 13, 3029–3036.

Wantiez, L., Chateau, O., Le Mouellic, S., 2006. Initial and mid-term impacts of cyclone Erica on coral reef fish communities and habitat in the south Lagoon Marine Park of New Caledonia. Journal of the Marine Biological Association of the United Kingdom 86, 1229–1236.

Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309, 1844–1846.

Yu, K.F., Zhao, J.X., Collerson, K.D., Shi, Q., Chen, T.G., Wang, P.X., Liu, T.S., 2004. Storm cycles in the last millennium recorded in Yongshu Reef, southern South China Sea. Palaeogeography, Palaeoclimatology, Palaeoecology 210, 89–100.

Yu, K.-F., Zhao, J.-X., Shi, Q., Chen, T.-G., Wang, P.-X., Collerson, K.D., Liu, T.-S., 2006a. U-series dating of dead *Porites* corals in the south China sea: evidence for episodic coral mortality over the past two centuries. Quaternary Geochronology 1, 129–141.

Yu, K.F., Zhao, J.X., Wang, P.X., Shi, Q., Meng, Q.S., Collerson, K.D., Liu, T.S., 2006b. High-precision TIMS U-series and AMS C-14 dating of a coral reef lagoon sediment core from southern south China Sea. Quaternary Science Reviews 25, 2420–2430.

Yu, K.-F., Zhao, J.-X., Shi, Q., Meng, Q.S., 2008. Reconstruction of storm/tsunami records over the last 4000 years using transported coral blocks and lagoon deposits in the southern South China Sea. Quaternary International, this volume. doi:10.1016/j.quaint.2008.05.004.

Zhao, J.X., Hu, K., Collerson, K.D., Xu, H.K., 2001. Thermal ionization mass spectrometry U-series dating of a hominid site near Nanjing, China. Geology 29, 27–30.

Zhao, J.X., Yu, K.F., Feng, Y.X., 2008. High-precision ^{238}U–^{234}U–^{230}Th disequilibrium dating of the recent past (0–500 years). Quaternary Geochronology, accepted for publication.