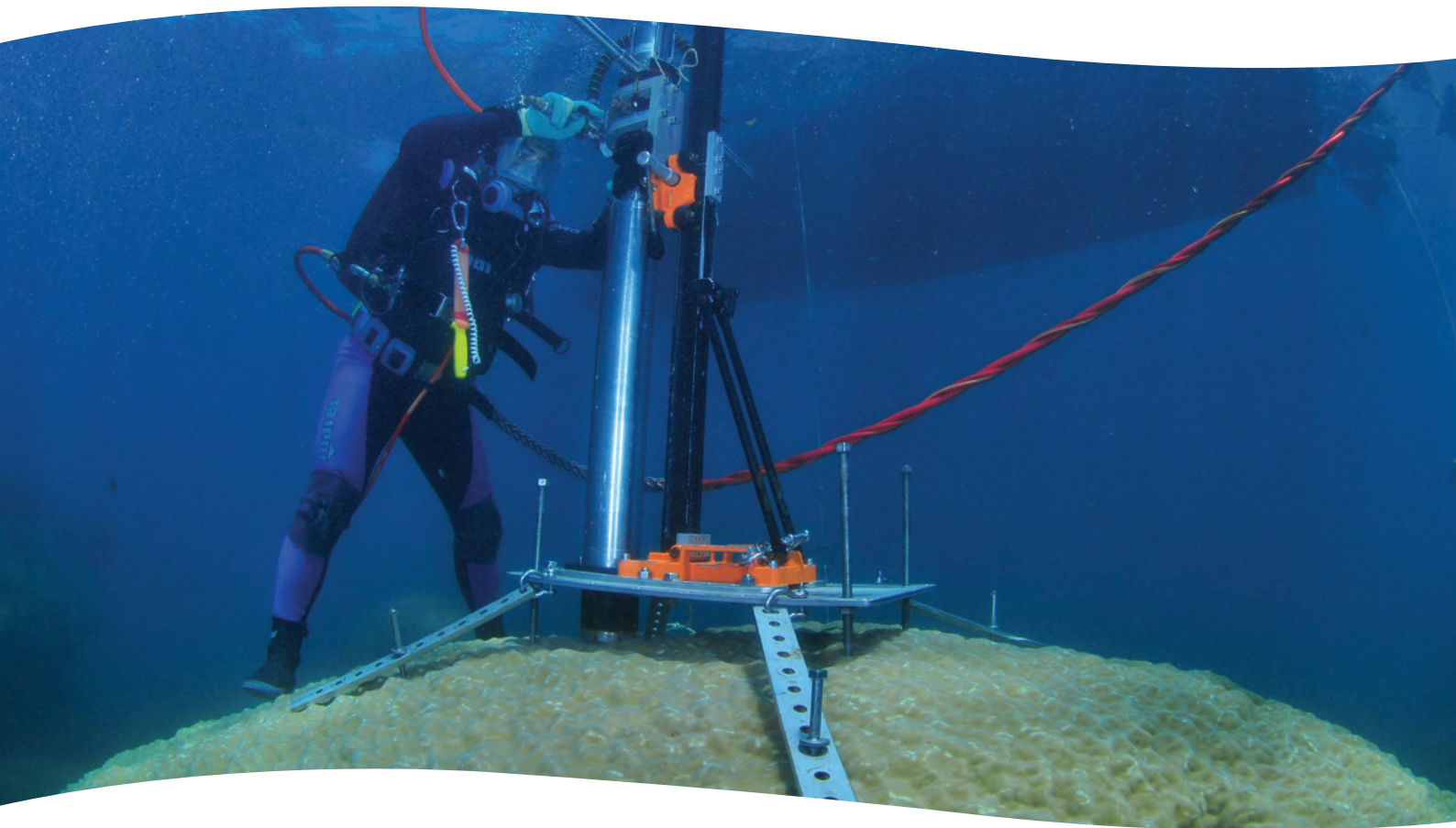


Coral Core Records of the North-east Torres Strait

Janice M. Lough



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Australian Institute of Marine Science



Supported by the Australian Government's
National Environmental Science Programme
Project 2.2.1: Identifying the water quality and ecosystem health threats to the high diversity Torres Strait and Far Northern GBR
from runoff from the Fly River

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CONTENTS

Contents.....	i
List of Tables.....	ii
List of Figures.....	iii
Acronyms	iv
Abbreviations	iv
Acknowledgements	iv
Executive Summary	v
1.0 Introduction	1
2.0 Materials and Methods	3
2.1 Coral Data.....	3
2.2 Climatic data and analysis	3
3.0 Results and Discussion	5
3.1 Annual coral growth characteristics.....	5
3.2 Coral luminescence and freshwater signatures	8
3.2.1 Bramble Cay.....	8
3.2.2 Darnley Island	9
3.2.3 Quantitative analysis of luminescence in BRM03C: 1781-1994	9
4.0 Conclusions.....	13
References.....	14
Appendix A.....	16

LIST OF TABLES

Table 1:	Annual average growth characteristics ($\pm$ sd) for three Torres Strait cores for the common period, 1939-1986 and average, minimum and maximum values for each variable based on 35 GBR long cores for common period, 1933-1982 (from Lough et al., 1999).	5
Table A1:	Annual linear extension (cm.yr^{-1}), skeletal density (g.cm^{-3}), calcification ($\text{g.cm}^{-2}.\text{yr}^{-1}$) and luminescence range (no units) for BRM02B, BRM03C and DNL02B. The green shading of luminescence range values indicates years where UV photos shows some distortion/disruption. Also shown for BRM03C is the annual number of luminescent lines visible each year (S = single, D = double, T = triple, M = multiple).	16

LIST OF FIGURES

Figure 1:	Google Earth image showing locations of two coral coring sites – Bramble Cay (BRM) and Darnley Island (DNL).	1
Figure 2:	Annual average <i>Porites</i> calcification rate vs. annual average sea surface temperature (1961-1990) for 49 Indo-Pacific sites (grey diamonds; Lough 2008). Dashed line is linear regression for these 49 sites. Also shown are average calcification rates (1961-1990) for BRM02B (blue triangle), BRM03C (green circle) and DNL02B (red square) vs. average annual sea surface temperature for 9.5°S, 143.5°E (HadISST).	6
Figure 3:	Annual anomalies from 1939-1986 mean for a) BRM02B calcification, b) BRM03C calcification, c) DNL02B calcification and d) sea surface temperature 9.5°S, 143.5°E. Thick line is 11-year Gaussian filter emphasising decadal variability. Linear regression shown for SST.	7
Figure 4:	Example of where patterns of luminescent lines match (cross-date) between BRM02B and BRM03C. Note the two corals do not exactly align due to difference in linear extension rates.	9
Figure 5:	Anomalies from 1939-1986 mean for annual luminescence range for BRM03C, 1782-1994. Thick line is 11-year Gaussian filter emphasising decadal variability.	10
Figure 6:	Fly River catchment monthly median rainfall, 1901-1912. Error bars denote 90th and 10th percentiles.	11
Figure 7:	Fly River catchment annual (December-November) rainfall, 1902-2012. Grey dashed line is median and dark line is 10-year Gaussian filter to emphasise decadal variability.	11
Figure 8:	Median monthly values for 9 La Niña events, 7 El Niño events and long-term median for a) SST and b) Fly River catchment rainfall.	12
Figure A1:	a) X-ray positive prints and b) digitally-enhanced photographs under UV light of coral slices for 2 sections of BMR02B.	21
Figure A2:	a) X-ray positive prints and b) digitally-enhanced photographs under UV light of coral slices for 6 sections of BMR03C	22
Figure A3:	a) X-ray positive prints, and b) digitally-enhanced photographs under UV light of coral slices for 4 sections of DNL02B.	23
Figure A4:	Example positive X-ray prints of Great Barrier Reef coral core slices showing annual density banding and digitally-enhanced photographs under UV light showing luminescent lines and bands.	24

ACRONYMS

AIMS Australian Institute of Marine Science
ENSO El Niño-Southern Oscillation
GBR Great Barrier Reef
NESP National Environmental Science Programme
SST Sea Surface Temperature
TWQ Tropical Water Quality

ABBREVIATIONS

CaCO₃ Calcium carbonate

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Thanks to Eric Matson, AIMS, for technical assistance.

EXECUTIVE SUMMARY

Annual massive coral growth and luminescence records were visualised by X-ray and UV images in slices from three coral cores from Darnley Island and Bramble Cay in the northern Torres Strait. The longest and most reliable of these records (BRM03C) covers the period 1781-1993. Annual coral growth rates for all three cores are typical of massive *Porites* corals living in the average sea surface temperatures of the northern Torres Strait. There is no evidence of growth hiatuses in any of the cores that might be associated with environmental stress events. Luminescent lines (indicative of freshwater flood plumes) are evident in both corals from Bramble Cay but not the coral from Darnley Island. At Bramble Cay, there are usually several pulses of freshwater each year, likely associated with atmospheric or oceanic processes pushing the freshwater onto the reef. These pulses of freshwater are evident back to 1781. El Niño-Southern Oscillation events also result in marked differences in rainfall (and hence Fly River flow) and sea surface temperature (SST) in the northern Torres Straits.

1.0 INTRODUCTION

The backbone of tropical coral reef ecosystems is sustained production of CaCO_3 skeletons (calcification), which withstand the natural forces of physical and biological erosion and provide the structural complexity to support the many thousands of reef-associated organisms characteristic of a healthy reef. Certain massive corals, such as *Porites* spp., contain annual variations in the density of CaCO_3 skeleton revealed in X-rays of slices of the coral (Knutson et al., 1972). These annual density bands consist of a high density band, usually formed in summer and a low density band, usually formed in winter. As some corals continuously form skeleton over many years, these natural, dateable archives can provide insights into coral growth and environmental conditions (through various tracers incorporated into the skeleton) over tens to hundreds of years (Lough, 2010).

In this component of the National Environmental Science Programme (NESP) Tropical Water Quality (TWQ) Hub Project 2.2.1 skeletal luminescence (as a proxy for freshwater/river flow, Lough et al. 2002, 2015) and skeletal density (to derive annual growth characteristics, Lough and Cooper 2011) were measured in slices from three *Porites* coral cores from the Australian Institute of Marine Science (AIMS) Coral Core Archive. Two cores were from Bramble Cay (Maizab Kaur) at the northeastern edge of the Torres Strait Islands, ~55km southeast of the mouth of the Fly River and one core from Darnley Island (Erub), ~46km southwest of Bramble Cay in the eastern section of Torres Strait (Figure 1).

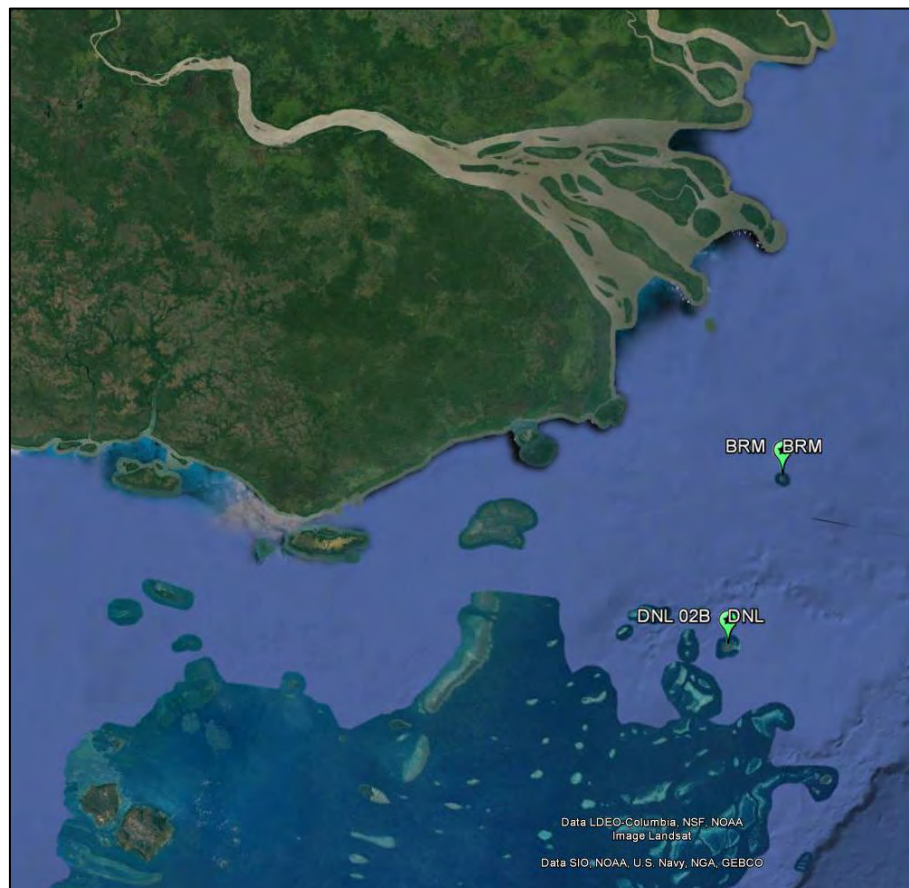


Figure 1: Google Earth image showing locations of two coral coring sites – Bramble Cay (BRM) and Darnley Island (DNL).

The objectives were:

- 1) Develop chronologies of annual coral growth rates from the two reef sites
- 2) Determine whether freshwater from the Fly River was regularly recorded as luminescent lines in the Bramble Cay cores to provide an historical record of the Fly River in the northeastern Torres Strait
- 3) Whether luminescent lines, indicative of Fly River water, were occasionally evident at Darnley Island (Wolanski et al., 1999)
- 4) Document trends and variability in Torres Strait sea surface temperatures (SST) and Fly River catchment rainfall based on instrumental records and the influence of the primary source of inter-annual tropical climate variability, El Niño-Southern Oscillation (ENSO) events, on regional climate (Australian Bureau of Meteorology and CSIRO, 2011).

2.0 MATERIALS AND METHODS

2.1 Coral Data

Coral cores were collected by AIMS using an underwater pneumatic drilling rig (Isdale and Daniel, 1989) from one *Porites* colony at Darnley Island (9.58°S, 143.77°E, AIMS core ID: DNL02B) in September 1986 and two *Porites* colonies at Bramble Cay (9.13°S, 143.88°E, AIMS core IDs: BRM02B and BRM03C) in February 1994. Cores were collected vertically from the top of each colony. Holes left in the colonies after coring were sealed with a concrete plug which is normally subsequently overgrown by the living tissue layer (Matson, 2011). Cores were 7 cm in diameter and retrieved in ~70-80 cm lengths (Lough et al., 1999). The total lengths of the cores were 2.7 m (DNL02B), 1.1 m (BRM02B) and 3.1 m (BRM03C), respectively. Core sections were then mounted and two to three 6-7 mm thick slices were sawn from close to their central axis.

Each core slice was X-rayed and the X-ray converted to a positive print to reveal the annual density banding pattern and identify the optimum track for measurement of skeletal density. Each slice was also photographed under UV light to reveal patterns of luminescent banding and lines. The depth of the living tissue layer at the outer edge of the core slice was also measured (Barnes and Lough, 1992).

Skeletal density was measured in 0.25 mm steps using gamma densitometry along a linear track of the slice from each core showing clearest presentation of annual density bands (Chalker and Barnes, 1990). At the same time, the intensity of luminescence along the core slice was measured using AIMS' custom built gamma densitometer/luminometer (Barnes et al., 2003). Based on the annual high density band forming in summer and the annual low density band in winter, successive density peaks were dated from the outer core edge relative to the date of collection of the core. Once dated, the following annual growth variables were extracted from the density vs. distance measurements for each core: 1) annual linear extension (cm.yr^{-1}), measured as the linear distance between adjacent density minima, 2) annual average skeletal density (g.cm^{-3}), measured as the average skeletal density between adjacent density minima, and 3) annual calcification rate ($\text{g.cm}^{-2}.\text{yr}^{-1}$), calculated as the product of annual linear extension and average annual density. Where possible (see Results), annual luminescent lines were dated from the outer edge of each slice and the annual luminescence range (difference between summer peak luminescence and previous winter luminescence minimum) was calculated. This range is the most robust luminescence metric of freshwater flow affecting a reef (Lough, 2011a) and has been used, for example, to reconstruct Queensland rainfall back to the 17th century (Lough, 2011b).

2.2 Climatic data and analysis

Monthly SST data for the period 1871-2015 were obtained from the HadISST data set (www.metoffice.gov.uk/hadobs/hadisst/; Rayner et al., 2003) for the 1-degree latitude x longitude box encompassing Bramble Cay and Darnley Island (9.5°S, 143.5°E) and the four 1-degree latitude x longitude boxes encompassing the Torres Strait (9.5°-10.5°S, 142.5°-143.5°E).

Monthly rainfall data for the period 1901-2012 were obtained from the Climatic Research Unit CRU TS 3.21 (<https://climatedataguide.ucar.edu/climate-data/cru-ts321-gridded-precipitation-and-other-meteorological-variables-1901>) grid-point data set averaged for the region approximating the Fly River catchment (4.75°-8.75°S, 140.75°-143.75°E).

To assess the typical influence of ENSO on regional rainfall and SST, in the period post-1950 (when instrumental data is most reliable; Jones, 2016) median monthly rainfall and SST were calculated for strong El Niño and La Niña events for the 24-month period from January of the first year of an event through December of the second year (e.g. January 1997 through December 1998). Selection of seven strong El Niño and nine strong La Niña events was based on the May-April value of the Niño 3.4 index of ENSO (www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php). The El Niño events (average Niño 3.4 index = $+1.16 \pm 0.37^\circ\text{C}$) were: 1957-58, 1965-66, 1972-73, 1982-83, 1986-87, 1991-92 and 1997-98. The La Niña events (average Niño 3.4 index = $-1.05 \pm 0.21^\circ\text{C}$) were: 1955-56, 1970-71, 1973-74, 1975-76, 1988-89, 1999-00, 2007-08 and 2010-11.

3.0 RESULTS AND DISCUSSION

3.1 Annual coral growth characteristics

Annual density bands in slices from massive coral skeletons are not always clearly presented in different cores and along the length of an individual core due to convolutions in skeletal architecture in relation to the major growth axis (Lough and Barnes, 1992). This can affect the confidence in annual density band dating and the precision of the derived growth measurements. The two cores from Bramble Cay had relatively clearly presented annual density bands along their length (Figures A1a and A2a) and the annual density bands were dated with good confidence. In contrast clear identification of annual density bands in DNL02B varied along the length of the core due to convolutions in skeletal growth (Figure A3a) and confidence in dating the annual bands was lower. Dated annual growth records were obtained for the period 1781-1993 for BRM03C, 1939-1993 for BRM02B and 1831-1986 for DNL02B, respectively. There was no evidence in the X-ray prints of the three cores of any growth hiatuses or partial mortality that are characteristic of thermal stress events (see X-ray positive print examples from the GBR in Figures A4 b, c and d (from Cantin and Lough, 2014).

Annual coral growth variables for the three cores are presented in Table A1 and average characteristics for the common period, 1939-1986 in Table 1. The average and range of coral growth characteristics for 35 long *Porites* cores from the length of the Great Barrier Reef (GBR; from Lough et al., 1999) are also presented for comparison. All three Torres Strait corals have growth rates within the range observed for the GBR. BRM02B has quite low tissue layer thickness but high linear extension and calcification rates. BRM03C and DNL02B have lower linear extension rates but higher skeletal density. Calcification rates, the product of linear extension and skeletal density, are, however, comparable amongst the three cores. They are also close (within 5-10%) of the calcification rate expected from the strong linear relationship between average calcification rates and average annual SST of Indo-Pacific *Porites* (Figure 2; Lough, 2008), i.e. over the time period of the analysis these three corals are calcifying at the expected rates given the average thermal environment (27.5°C).

Table 1: Annual average growth characteristics ($\pm$ sd) for three Torres Strait cores for the common period, 1939-1986 and average, minimum and maximum values for each variable based on 35 GBR long cores for common period, 1933-1982 (from Lough et al., 1999).

	Total period	Tissue thickness (mm)	Extension (cm.yr ⁻¹)	Density (g.cm ⁻³)	Calcification (g.cm ⁻² .yr ⁻¹)
BRM02B	1939-1993	4.5	1.82 $\pm$ 0.30	1.20 $\pm$ 0.09	2.17 $\pm$ 0.34
BRM03C	1781-1993	6.8	1.30 $\pm$ 0.27	1.49 $\pm$ 0.08	1.94 $\pm$ 0.42
DNL02B	1831-1986	7.8	1.23 $\pm$ 0.40	1.54 $\pm$ 0.05	1.90 $\pm$ 0.61
GBR 35 cores average	1934-1982	7.3	1.48	1.17	1.72
GBR 35 cores (min and max)		(4.6-9.8)	(0.88-2.17)	(0.98-1.39)	(1.14-2.49)

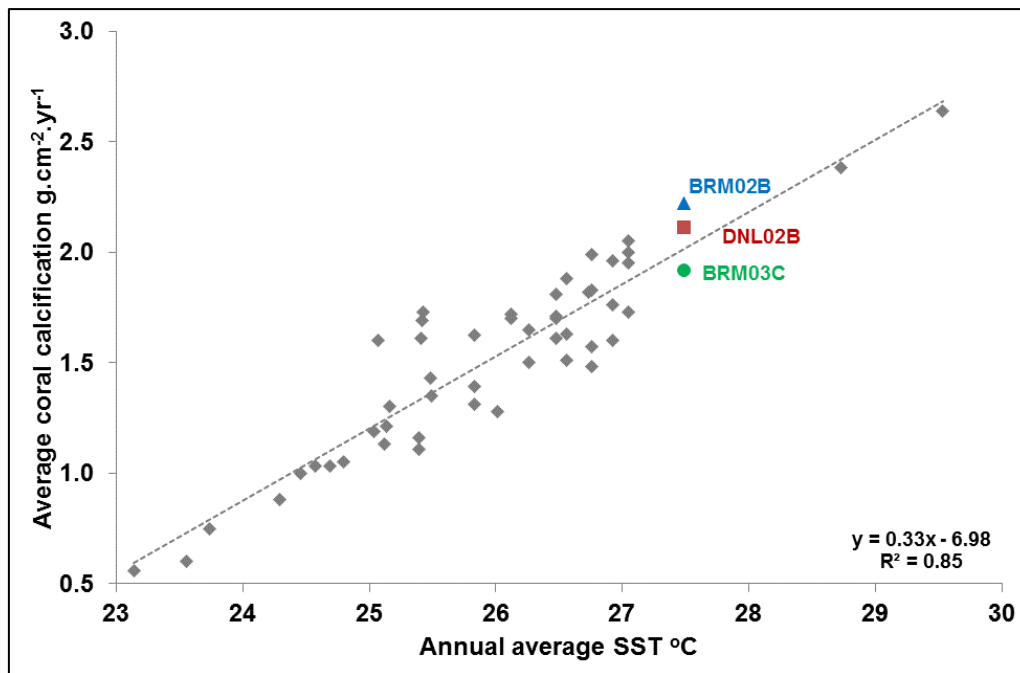


Figure 2: Annual average *Porites* calcification rate vs. annual average sea surface temperature (1961-1990) for 49 Indo-Pacific sites (grey diamonds; Lough 2008). Dashed line is linear regression for these 49 sites. Also shown are average calcification rates (1961-1990) for BRM02B (blue triangle), BRM03C (green circle) and DNL02B (red square) vs. average annual sea surface temperature for 9.5°S, 143.5°E (HadISST).

Annual calcification rate anomalies (from 1939-1986 mean) are presented along with instrumental SST anomalies in Figure 3. All three cores show substantial interannual and decadal variability but no significant long-term trends to either higher or lower calcification rates nor are there similar patterns amongst the three colonies. In contrast SST anomalies show a significant warming trend, 1871-2015 of 0.03°C/decade and overall warming of 0.39°C. The warmest years on record were 1998 and 2010. Thus calcification rates for the three corals fluctuate over the respective record periods and are not coupled with SST warming in the region (e.g. for common period 1939-1986 SST significantly warmed by 0.27°C ($r^2 = 11.5\%$, $p = 0.018$)) but there were no significant trends in any of the three cores.

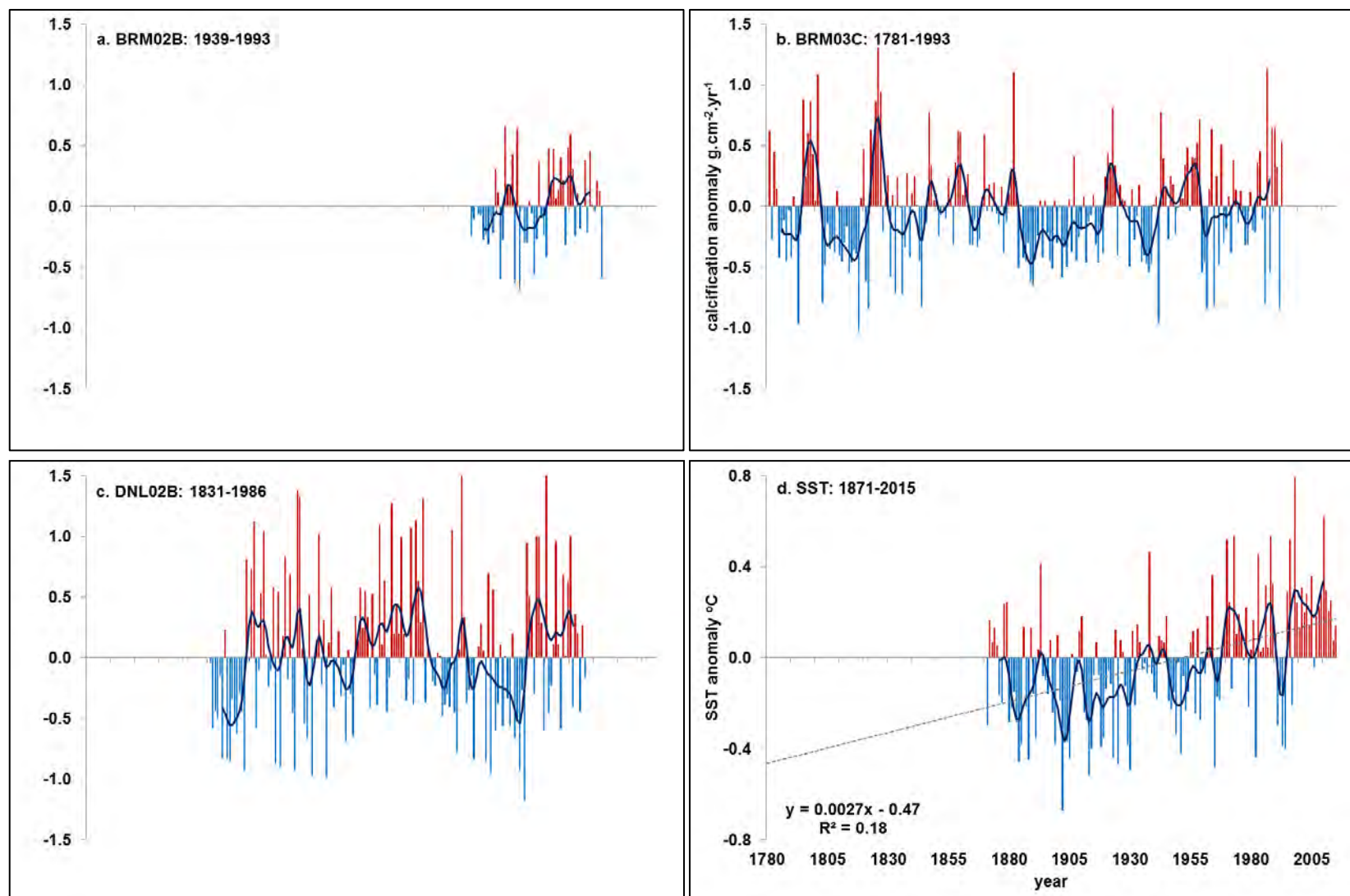


Figure 3: Annual anomalies from 1939-1986 mean for a) BRM02B calcification, b) BRM03C calcification, c) DNL02B calcification and d) sea surface temperature 9.5°S, 143.5°E. Thick line is 11-year Gaussian filter emphasising decadal variability. Linear regression shown for SST.

3.2 Coral luminescence and freshwater signatures

The appearance of luminescent lines and bands, made visible when coral slices are viewed under UV light, can provide insights into freshwater river flood plumes affecting a reef (Lough et al., 2002). Inshore corals of the GBR, for example, typically show bright luminescent lines which reflect the occurrence and intensity of freshwater flood plumes affecting the reef (see UV photos in Figure A4a and b). Midshelf reefs typically show background luminescent banding and an occasional bright luminescent line associated with very large river flood events where the freshwater plume was extensive enough to reach the reef (see UV photo of 1991 luminescent line associated with a flood plume at Rib Reef, ~60 km from land, Figure A4c). At offshore reefs, never influenced by freshwater flood waters, coral slices under UV only display faint luminescent bands associated with the annual variations in skeletal density (Barnes and Taylor, 2001; see UV photo Figure A4d). The annual (inshore) and occasional (midshelf) luminescent lines related to freshwater flood plumes are due to the incorporation of terrestrial humic acids into the coral skeleton (see discussion in Llewellyn et al., 2012). This prior understanding and experience of luminescent lines and bands in *Porites* corals from throughout the GBR guided the following assessment of the nature of luminescent patterns in the three Torres Strait cores as viewed under UV light.

3.2.1 Bramble Cay

Luminescent lines, characteristic of freshwater influence, are visible in BRM02B (Figure A1b) but their appearance is obscured in places: from ~31-51 cm in section 01 and from ~25-45 cm in section 02). This blurring of the appearance of luminescence is not obviously associated with any features in the X-ray positives (Figure A1a) which might have linked it with early marine diagenesis (e.g. McGregor and Gagan, 2003). The origin of this blurring is unclear but has occasionally been observed in *Porites* corals from the GBR and Western Australian reefs in AIMS' Coral Core Archive. Where clearly visible and combined with the demarcation of annual growth bands from the X-ray positives of the same slice, the luminescent lines suggests that several pulses of freshwater affect the coral each year rather than a single or occasional double flood peak that characterises inshore corals of the GBR (c.f. Figure A4).

Luminescent lines, characteristic of freshwater influence, are also visible in BRM03C and are well displayed along the length of the core (Figure A2b). As with BRM02B, luminescence in this core is characterised by often multiple lines each year. That these lines are reflecting a common environmental signal (i.e. freshwater pulses) is confirmed by evidence of similar patterns of luminescent lines in BRM03C and BRM02B (Figure 4).

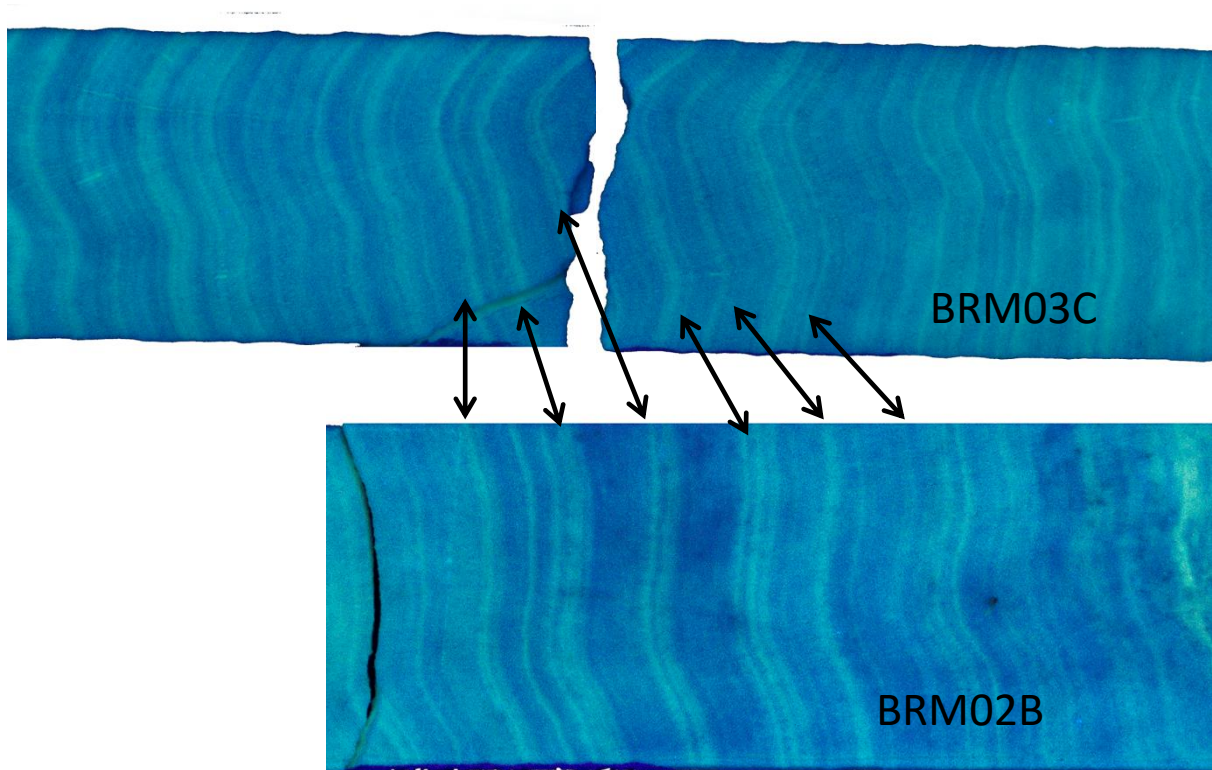


Figure 4: Example of where patterns of luminescent lines match (cross-date) between BRM02B and BRM03C. Note the two corals do not exactly align due to difference in linear extension rates.

This ability to cross-date the two corals provides strong support that BRM03C is recording Fly River runoff for the measurable length of the core and is analysed further below. It is, however, likely that the appearance of these luminescent lines at Bramble Cay is a result of the complex oceanographic drivers of water circulation in the region driving pulses of freshwater onto the reef (e.g. Wolanski et al., 1999; Martin and Wolanski, 2015) rather than being directly related to the volume discharge of the Fly River, which is a year round phenomenon.

3.2.2 Darnley Island

Under UV light DNL02B also showed (similar to BRM02B) sections where the appearance of the luminescence was blurred: between ~ 10-34 cm in section 01, between ~28-46 cm in section 02 and between ~ 17-34 cm in section 03 (Figure A3b). In contrast to the two Bramble Cay cores, the core from Darnley Island did not show any luminescent lines characteristic of freshwater influence, only broad, faint background luminescent bands characteristic of offshore reefs (e.g. Myrmidon Reef Figure A4d). If pulses of freshwater were occasionally affecting Darnley Island marked luminescent lines would be expected to be visible (e.g. Rib Reef Figure A4c). The core was collected from the northward facing Treacherous Bay of Darnley Island with water depth to the top of the bommie of ~ 2m. So, if freshwater was impacting Darnley Island, the core was collected from an ideal location to record it. The conclusion is based on data for the period 1831-1984.

3.2.3 Quantitative analysis of luminescence in BRM03C: 1781-1994

For inshore corals from the GBR, the annual luminescence range (difference between summer maximum and previous winter minimum) is the most robust measure of river flow that also

circumvents a long-term age-related decline in average luminescence (probably related to a similar decline in skeletal density; Lough, 2011a). Although luminescent lines (frequently multiple lines) are evident annually at Bramble Cay these are likely to reflect oceanographic processes forcing pulses of freshwater on to Bramble Cay rather than being directly related to the volume discharge of the Fly River itself. Thus, the luminescence range for BRM03C (Figure 5) is unlikely to be a simple measure of the volume of Fly River runoff affecting the Bramble Cay. This time series, combined with the visual appearance of luminescent lines (Figure A2b) does, however, present strong evidence that freshwater pulses from the Fly River annually reach Bramble Cay and this is evidence back to 1781.

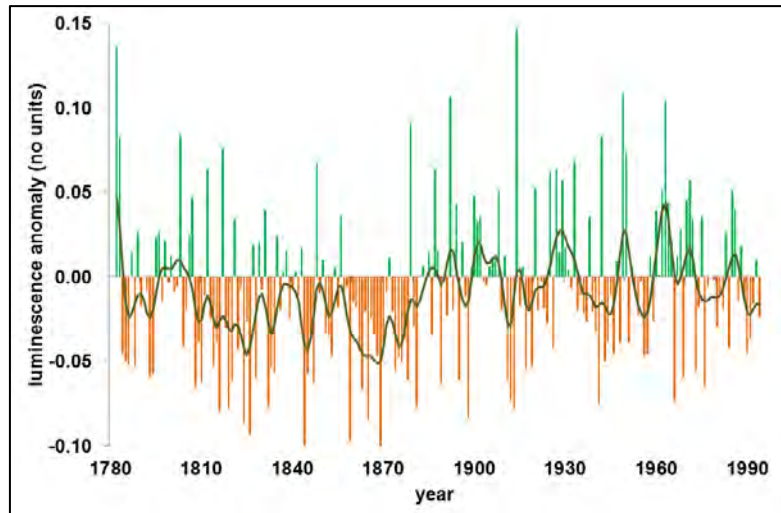


Figure 5: Anomalies from 1939-1986 mean for annual luminescence range for BRM03C, 1782-1994. Thick line is 11-year Gaussian filter emphasising decadal variability.

Regional climate variation and ENSO

Fly River catchment rainfall, 1901-1912, is higher December to May (median = 1,968 mm; ~60% of annual total) and lower June to November (median = 1,345 mm; ~40% of annual total) (Figure 6). March tends to be the wettest month and September the driest.

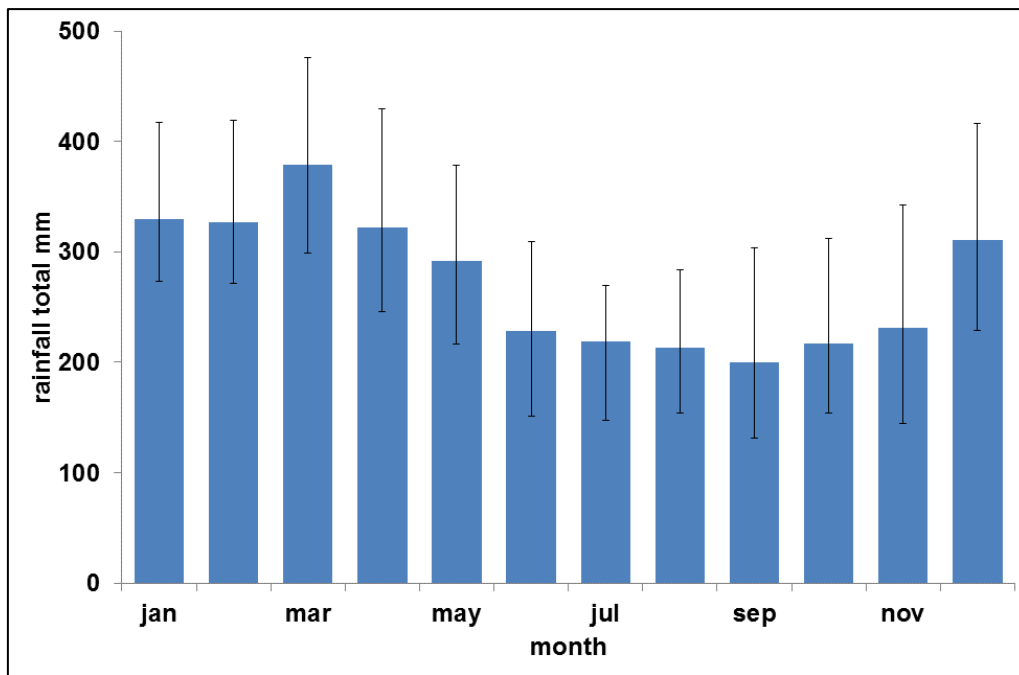


Figure 6: Fly River catchment monthly median rainfall, 1901-1912. Error bars denote 90th and 10th percentiles.

Median rainfall for December-November, 1902-2012 was 3,323 mm with a coefficient of variation of 10.3%. Maximum rainfall occurred in 1971 with 4,160 mm (125% of median rainfall) and minimum rainfall in 1982 with 2,387 mm (72% of median). So, although rainfall occurs year round in the Fly River catchment there are relatively wetter (December to May) and drier (June to November) seasons. There was no long-term trend in rainfall, 1901-1912 (Figure 7).

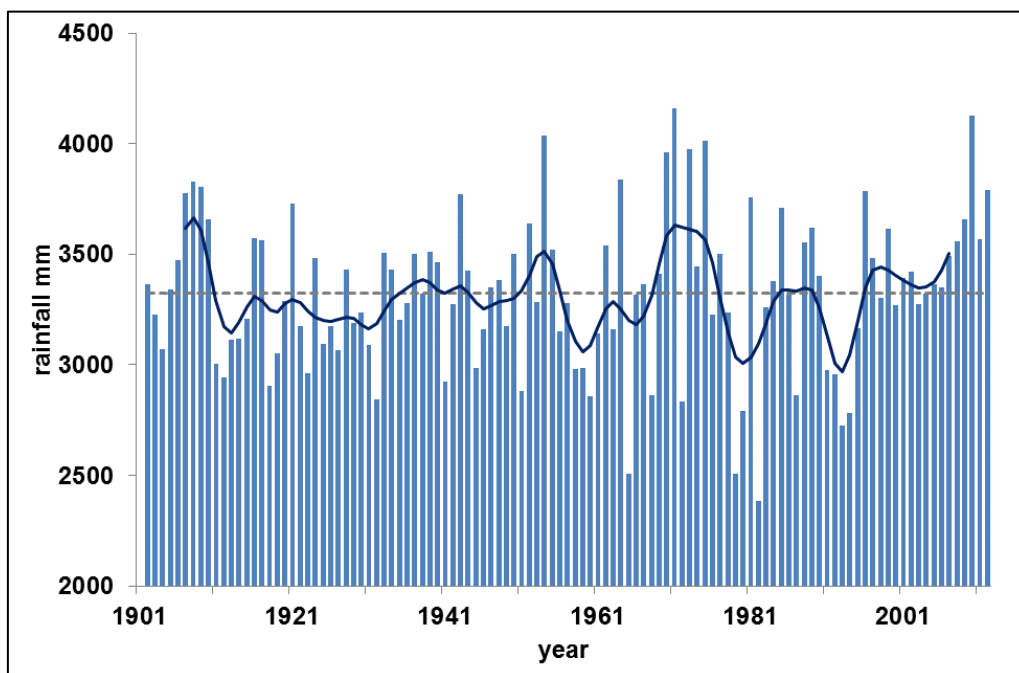


Figure 7: Fly River catchment annual (December-November) rainfall, 1902-2012. Grey dashed line is median and dark line is 10-year Gaussian filter to emphasise decadal variability.

Composite analysis of SST (c.f. Lough, 2007) shows that during El Niño events Torres Strait SST are typically below median in June–November of the first year and warmer than median January to March of the second year (Figure 8a). During La Niña events August to December SST of the first year tend to be warmer than median.

For Fly River catchment rainfall (Figure 8b), La Niña events tend to have above median rainfall from September to December of the first year, while El Niño events have drier conditions from May to December of the first year. Over the 24-month period La Niña events tend to be associated with +384mm of rainfall (compared to monthly medians) and El Niño events -443 mm.

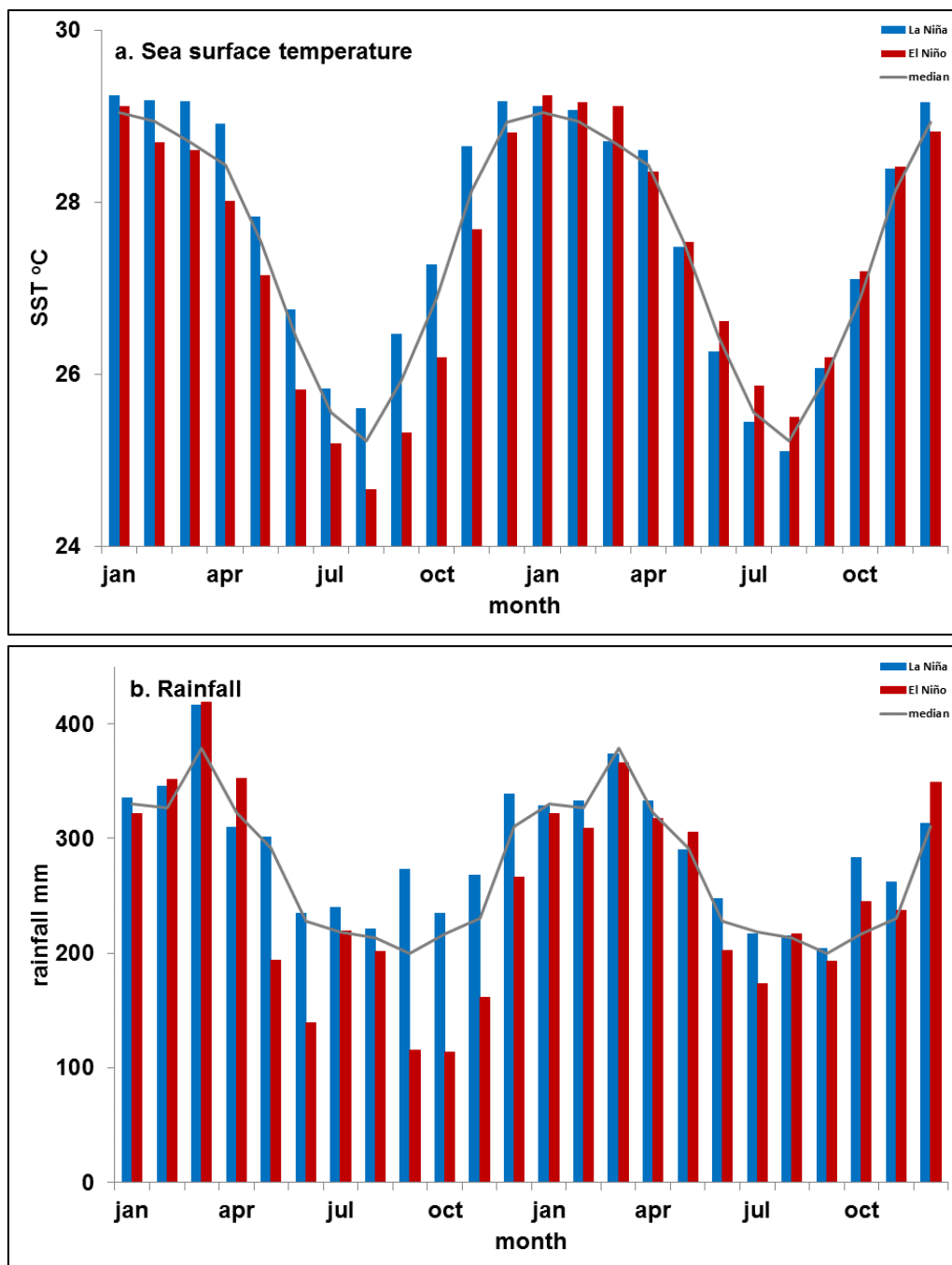


Figure 8: Median monthly values for 9 La Niña events, 7 El Niño events and long-term median for a) SST and b) Fly River catchment rainfall.

4.0 CONCLUSIONS

- Average calcification rates at Darnley Island and Bramble Cay are as expected for the average annual SST of these sites.
- There are interannual and decadal variations in calcification rates at both sites but no variations linked with significant warming of SST
- There is no evidence of any growth hiatuses (indicative of stress) in the annual density bands of the three cores.
- La Niña events tend to be associated with higher rainfall totals and El Niño events with lower rainfall totals in the Fly River catchment
- January to March SST tend to be warmer in the northern Torres Strait during El Niño years
- Characteristic luminescent lines indicate that Bramble Cay is annually influenced by freshwater from the Fly River. There are frequently several pulses of freshwater each year and such annual influence is evident in the longer core (BRM03C) for the period 1781-1994.
- In contrast, the coral core from Darnley Island provides no evidence for even occasional freshwater reaching this reef over the period 1831-1984.

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APPENDIX A

Table A1: Annual linear extension (cm.yr⁻¹), skeletal density (g.cm⁻³), calcification (g.cm⁻².yr⁻¹) and luminescence range (no units) for BRM02B, BRM03C and DNL02B. The green shading of luminescence range values indicates years where UV photos shows some distortion/disruption. Also shown for BRM03C is the annual number of luminescent lines visible each year (S = single, D = double, T = triple, M = multiple).

Year	BRM02B				BRM03C					DNL02B			
	Ext	Den	Calc	Lum	Ext	Den	Calc	Lum	# lines	Ext	Den	Calc	Lum
1781					1.63	1.58	2.56		D				
1782					0.99	1.68	1.67	0.271	S				
1783					1.42	1.68	2.39	0.217	D				
1784					1.27	1.64	2.09	0.089	S				
1785					0.94	1.62	1.52	0.085	T				
1786					1.09	1.58	1.72	0.083	D				
1787					1.17	1.56	1.82	0.149	S				
1788					0.97	1.54	1.49	0.082	T				
1789					1.30	1.48	1.91	0.161	S				
1790					1.07	1.43	1.53	0.118	D				
1791					1.35	1.50	2.02	0.135	D				
1792					1.12	1.48	1.65	0.127	D				
1793					0.69	1.42	0.97	0.076	S				
1794					1.12	1.53	1.71	0.077	S				
1795					1.65	1.71	2.82	0.158	S				
1796					1.27	1.73	2.19	0.161	D				
1797					1.46	1.74	2.54	0.120	D				
1798					1.65	1.70	2.80	0.156	T				
1799					1.42	1.67	2.37	0.131	S				
1800					1.19	1.66	1.98	0.147	D				
1801					1.85	1.63	3.02	0.126	T				
1802					1.25	1.68	2.09	0.129	D				
1803					0.66	1.74	1.15	0.219	S				
1804					0.86	1.69	1.46	0.094	S				
1805					1.07	1.69	1.80	0.115	S				
1806					0.94	1.70	1.60	0.160	S				
1807					0.97	1.71	1.65	0.182	S				
1808					0.91	1.71	1.56	0.070	S				
1809					1.19	1.73	2.06	0.096	D				
1810					0.89	1.73	1.54	0.072	M				
1811					0.86	1.72	1.49	0.123	S				
1812					1.02	1.62	1.64	0.199	T				
1813					1.12	1.59	1.77	0.110	S				
1814					0.94	1.49	1.40	0.082	S				
1815					0.97	1.53	1.48	0.096	S				
1816					1.07	1.48	1.58	0.055	D				
1817					1.14	1.36	1.55	0.211	S				
1818					0.66	1.39	0.92	0.104	M				
1819					1.37	1.47	2.01	0.057	S				
1820					1.60	1.51	2.41	0.073	S				
1821					0.84	1.58	1.33	0.169	D				
1822					0.71	1.55	1.10	0.092	D				
1823					1.55	1.66	2.57	0.127	S				
1824					1.50	1.62	2.43	0.048	M				
1825					1.71	1.64	2.80	0.108	D				
1826					1.93	1.68	3.25	0.041	M				

Year	BRM02B				BRM03C					DNL02B			
	Ext	Den	Calc	Lum	Ext	Den	Calc	Lum	# lines	Ext	Den	Calc	Lum
1827					1.73	1.67	2.88	0.154	S				
1828					1.04	1.66	1.73	0.075	D				
1829					1.22	1.65	2.01	0.155	D				
1830					1.37	1.60	2.19	0.127	D				
1831					0.89	1.54	1.36	0.174	D	1.25	1.49	1.85	
1832					1.25	1.63	2.03	0.058	D	0.86	1.53	1.32	0.053
1833					0.81	1.51	1.23	0.081	D	0.97	1.52	1.47	0.063
1834					1.37	1.59	2.18	0.078	S	0.91	1.52	1.39	0.088
1835					1.19	1.61	1.93	0.159	S	1.09	1.60	1.74	0.175
1836					0.79	1.55	1.22	0.115	S	0.66	1.61	1.06	0.086
1837					1.02	1.58	1.60	0.138	D	1.35	1.58	2.12	0.076
1838					1.35	1.64	2.21	0.150	S	0.66	1.61	1.06	0.074
1839					0.94	1.62	1.52	0.110	T	0.66	1.58	1.04	0.092
1840					1.25	1.65	2.05	0.129	D	0.99	1.57	1.56	0.045
1841					1.27	1.72	2.19	0.138	D	0.84	1.61	1.35	0.071
1842					1.17	1.67	1.95	0.124	D	0.79	1.62	1.27	0.108
1843					0.91	1.64	1.50	0.152	S	0.99	1.62	1.61	0.070
1844					0.69	1.62	1.11	0.034	S	0.91	1.59	1.45	0.050
1845					1.14	1.55	1.77	0.077	D	0.64	1.52	0.96	0.134
1846					1.19	1.51	1.80	0.102	S	1.70	1.59	2.71	0.068
1847					1.78	1.53	2.72	0.072	D	1.14	1.63	1.87	0.048
1848					1.51	1.51	2.28	0.202	S	1.70	1.54	2.63	0.057
1849					1.25	1.60	1.99	0.125	D	2.08	1.45	3.02	0.213
1850					1.32	1.55	2.05	0.145	S	0.94	1.41	1.32	0.119
1851					1.07	1.59	1.69	0.102	M	1.27	1.41	1.79	0.236
1852					1.22	1.53	1.87	0.100	S	1.61	1.51	2.43	0.041
1853					1.27	1.50	1.91	0.088	D	1.96	1.51	2.94	0.090
1854					1.19	1.54	1.84	0.140	S	1.27	1.51	1.92	0.085
1855					1.40	1.55	2.17	0.117	M	1.09	1.52	1.66	0.070
1856					1.30	1.55	2.01	0.171	T	1.14	1.57	1.79	0.048
1857					1.12	1.45	1.62	0.125	D	1.52	1.62	2.48	0.068
1858					1.55	1.49	2.30	0.129	D	0.64	1.61	1.02	0.044
1859					1.60	1.60	2.56	0.038	D	1.47	1.66	2.44	0.172
1860					1.58	1.62	2.55	0.120	S	0.61	1.64	1.00	0.015
1861					1.27	1.60	2.04	0.117	D	1.27	1.63	2.07	0.265
1862					1.35	1.60	2.15	0.091	S	1.63	1.68	2.73	0.127
1863					1.40	1.58	2.20	0.068	D	1.04	1.65	1.72	0.102
1864					1.07	1.53	1.63	0.114	D	1.55	1.67	2.58	0.109
1865					1.04	1.56	1.62	0.050	S	0.84	1.72	1.44	0.056
1866					1.19	1.53	1.82	0.110	D	0.56	1.73	0.97	0.183
1867					1.09	1.48	1.61	0.101	S	1.91	1.72	3.28	0.253
1868					1.17	1.43	1.67	0.088	D	1.88	1.72	3.23	0.048
1869					1.32	1.53	2.02	0.031	D	1.14	1.72	1.97	0.126
1870					1.58	1.61	2.53	0.095	D	0.79	1.73	1.36	0.294
1871					1.19	1.60	1.91	0.126	S	0.71	1.73	1.23	0.223
1872					1.37	1.55	2.12	0.146	S	1.40	1.73	2.42	0.156
1873					1.19	1.59	1.90	0.114	D	0.53	1.73	0.92	0.092
1874					1.37	1.56	2.13	0.079	T	1.14	1.66	1.89	0.089
1875					1.19	1.58	1.88	0.087	M	1.27	1.61	2.05	0.132
1876					1.12	1.60	1.79	0.085	D	1.80	1.62	2.92	0.104
1877					1.30	1.62	2.10	0.098	D	1.04	1.61	1.67	0.077
1878					0.99	1.57	1.56	0.074	D	1.37	1.61	2.21	0.032
1879					1.14	1.59	1.81	0.226	D	0.56	1.62	0.91	0.082

Year	BRM02B				BRM03C					DNL02B			
	Ext	Den	Calc	Lum	Ext	Den	Calc	Lum	# lines	Ext	Den	Calc	Lum
1880					1.30	1.58	2.04	0.105	T	1.22	1.66	2.02	0.079
1881					1.35	1.67	2.25	0.058	T	1.52	1.62	2.47	0.080
1882					1.80	1.69	3.04	0.135	D	0.97	1.54	1.49	0.131
1883					1.41	1.53	2.15	0.141	T	1.14	1.60	1.83	0.131
1884					1.02	1.41	1.43	0.134	S	1.32	1.60	2.12	0.074
1885					1.37	1.43	1.96	0.149	D	0.99	1.59	1.58	0.065
1886					1.02	1.50	1.52	0.100	D	1.09	1.69	1.84	0.078
1887					0.99	1.50	1.49	0.198	S	0.76	1.59	1.21	0.031
1888					1.04	1.57	1.64	0.150	S	1.25	1.58	1.96	0.169
1889					0.86	1.53	1.32	0.071	D	1.02	1.57	1.60	0.116
1890					0.86	1.50	1.29	0.134	S	0.81	1.54	1.26	0.054
1891					1.04	1.45	1.51	0.112	D	1.42	1.58	2.24	0.042
1892					1.13	1.51	1.70	0.241	D	1.27	1.61	2.05	0.083
1893					1.22	1.63	1.99	0.115	S	1.50	1.65	2.47	0.110
1894					0.97	1.58	1.52	0.178	T	1.30	1.65	2.14	0.087
1895					1.25	1.60	1.99	0.074	S	1.45	1.69	2.45	0.056
1896					1.09	1.57	1.72	0.155	M	1.32	1.69	2.23	0.042
1897					0.94	1.59	1.50	0.123	D	0.91	1.63	1.49	0.053
1898					0.91	1.56	1.43	0.051	T	1.50	1.62	2.42	0.208
1899					1.27	1.57	1.99	0.140	D	1.22	1.44	1.76	0.054
1900					0.94	1.75	1.64	0.183	S	1.04	1.45	1.51	0.124
1901					1.12	1.73	1.93	0.167	T	2.06	1.46	2.99	0.054
1902					0.79	1.72	1.35	0.170	D	1.37	1.46	2.01	0.066
1903					0.94	1.71	1.61	0.132	D	1.68	1.52	2.54	0.085
1904					0.84	1.72	1.44	0.130	D	1.02	1.43	1.45	0.063
1905					1.17	1.71	2.00	0.141	D	1.19	1.45	1.73	0.096
1906					0.94	1.67	1.56	0.146	D	2.16	1.47	3.17	0.228
1907					1.42	1.65	2.35	0.145	S	1.37	1.53	2.09	0.104
1908					0.91	1.64	1.50	0.185	S	1.52	1.53	2.33	0.076
1909					1.04	1.61	1.68	0.115	D	1.35	1.56	2.10	0.090
1910					1.09	1.60	1.75	0.147	S	1.98	1.46	2.89	0.107
1911					1.25	1.63	2.02	0.074	D	1.42	1.47	2.10	0.290
1912					0.94	1.57	1.47	0.061	S	1.07	1.45	1.54	0.106
1913					1.14	1.59	1.82	0.057	D	1.17	1.47	1.72	0.076
1914					1.22	1.53	1.87	0.282	S	1.80	1.65	2.97	0.184
1915					1.30	1.57	2.03	0.118	S	0.94	1.61	1.51	0.139
1916					1.09	1.48	1.62	0.141	S	1.78	1.70	3.03	0.071
1917					1.04	1.42	1.47	0.080	D	1.50	1.69	2.53	0.088
1918					1.25	1.43	1.78	0.115	D	1.35	1.63	2.19	0.092
1919					1.07	1.45	1.55	0.082	S	2.06	1.56	3.21	0.062
1920					1.52	1.43	2.18	0.187	S	0.99	1.55	1.54	0.068
1921					1.60	1.48	2.37	0.115	D	1.27	1.62	2.06	0.092
1922					1.58	1.44	2.26	0.132	D	1.17	1.64	1.91	0.122
1923					1.80	1.53	2.75	0.116	D	1.04	1.63	1.70	0.063
1924					1.52	1.49	2.27	0.107	T	1.04	1.60	1.67	0.058
1925					1.02	1.51	1.54	0.197	S	1.22	1.59	1.93	0.052
1926					1.37	1.54	2.11	0.093	T	1.25	1.54	1.91	0.050
1927					1.30	1.54	2.00	0.198	D	0.97	1.47	1.42	0.074
1928					1.30	1.53	1.98	0.149	D	1.02	1.49	1.51	0.065
1929					1.27	1.53	1.94	0.192	S	1.09	1.46	1.59	0.076
1930					0.94	1.54	1.45	0.152	S	1.04	1.43	1.49	0.088
1931					1.35	1.55	2.08	0.139	S	2.01	1.47	2.95	0.079
1932					1.04	1.60	1.66	0.128	T	0.99	1.46	1.45	0.071

Year	BRM02B				BRM03C					DNL02B			
	Ext	Den	Calc	Lum	Ext	Den	Calc	Lum	# lines	Ext	Den	Calc	Lum
1933					1.17	1.59	1.86	0.203	S	0.76	1.47	1.12	0.068
1934					1.37	1.54	2.11	0.115	D	1.25	1.57	1.96	0.149
1935					1.07	1.39	1.49	0.124	T	2.24	1.61	3.60	0.115
1936					1.12	1.38	1.54	0.113	D	1.40	1.60	2.23	0.064
1937					1.04	1.41	1.47	0.108	D	0.94	1.62	1.52	0.037
1938					0.99	1.41	1.40	0.170	D	1.03	1.59	1.64	0.099
1939	1.47	1.31	1.93		0.99	1.48	1.47	0.114	S	1.12	1.57	1.75	0.112
1940	1.55	1.33	2.07	0.061	1.30	1.51	1.96	0.103	D	0.69	1.55	1.06	0.096
1941	1.60	1.36	2.18	0.084	1.37	1.48	2.03	0.059	D	1.19	12.58	1.89	0.048
1942	1.65	1.28	2.11	0.127	0.69	1.43	0.98	0.218	S	1.27	1.56	1.99	0.001
1943	1.73	1.22	2.10	0.129	1.83	1.49	2.72	0.085	M	1.40	1.56	2.18	0.078
1944	1.60	1.19	1.90	0.133	1.60	1.46	2.33	0.096	M	1.25	1.57	1.95	0.085
1945	1.73	1.13	1.95	0.060	1.40	1.51	2.11	0.124	D	0.66	1.58	1.05	0.113
1946	1.55	1.20	1.86	0.164	1.17	1.43	1.67	0.089	D	1.65	1.57	2.59	0.045
1947	1.70	1.23	2.09	0.176	1.47	1.49	2.19	0.144	M	0.61	1.55	0.94	0.103
1948	1.68	1.16	1.95	0.266	1.42	1.49	2.12	0.095	D	1.52	1.61	2.46	0.078
1949	2.16	1.15	2.48	0.288	1.17	1.47	1.71	0.244	S	0.81	1.59	1.30	0.095
1950	2.06	1.11	2.29	0.100	1.30	1.49	1.93	0.209	S	0.97	1.58	1.52	0.098
1951	1.32	1.20	1.58	0.179	1.32	1.56	2.06	0.096	D	1.30	1.55	2.00	0.081
1952	1.52	1.24	1.89	0.130	1.25	1.61	2.00	0.140	D	0.84	1.59	1.33	0.070
1953	2.34	1.22	2.84	0.090	1.37	1.66	2.28	0.124	T	1.19	1.60	1.91	0.055
1954	2.03	1.15	2.35	0.076	1.50	1.62	2.43	0.112	T	0.99	1.58	1.56	0.038
1955	2.06	1.14	2.35	0.255	1.22	1.56	1.90	0.132	T	0.84	1.58	1.33	0.057
1956	2.34	1.11	2.60	0.120	1.47	1.59	2.34	0.088	T	1.35	1.56	2.10	0.034
1957	1.40	1.10	1.54	0.062	1.50	1.56	2.34	0.089	D	0.79	1.56	1.23	0.029
1958	2.46	1.14	2.81	0.124	1.60	1.54	2.46	0.147	M	0.91	1.52	1.39	0.084
1959	1.30	1.16	1.50	0.116	1.78	1.50	2.66	0.108	D	0.66	1.47	0.97	0.096
1960	1.85	1.17	2.16	0.129	0.97	1.45	1.40	0.174	T	1.14	1.43	1.64	0.073
1961	1.65	1.14	1.88	0.127	1.04	1.42	1.48	0.136	D	0.48	1.49	0.72	0.065
1962	1.68	1.12	1.87	0.122	0.79	1.39	1.10	0.185	S	1.83	1.56	2.84	0.147
1963	2.08	1.06	2.22	0.124	1.40	1.49	2.08	0.239	D	1.52	1.58	2.41	0.107
1964	2.01	1.06	2.12	0.156	1.78	1.45	2.58	0.179	T	1.40	1.60	2.24	0.104
1965	1.58	1.03	1.62	0.148	0.79	1.43	1.13	0.156	T	1.02	1.58	1.60	0.185
1966	1.78	1.07	1.91	0.135	1.47	1.49	2.19	0.061	D	1.88	1.54	2.90	0.061
1967	2.36	1.08	2.54	0.098	1.04	1.40	1.46	0.147	T	1.98	1.46	2.89	0.103
1968	1.60	1.30	2.08	0.198	1.78	1.37	2.44	0.163	D	1.42	1.54	2.19	0.068
1969	1.49	1.30	1.94	0.107	1.19	1.37	1.64	0.076	M	0.86	1.51	1.30	0.102
1970	1.37	1.28	1.76	0.125	1.25	1.41	1.75	0.180	S	2.21	1.55	3.42	0.196
1971	2.16	1.23	2.65	0.126	1.40	1.45	2.02	0.192	D	0.97	1.49	1.44	0.120
1972	1.85	1.26	2.35	0.121	1.09	1.43	1.56	0.169	S	1.12	1.49	1.67	0.098
1973	2.13	1.24	2.65	0.166	1.65	1.40	2.32	0.079	S	1.27	1.58	2.01	0.086
1974	1.83	1.22	2.24	0.138	1.50	1.38	2.07	0.117	T	1.85	1.54	2.86	0.084
1975	1.91	1.21	2.31	0.105	1.27	1.42	1.80	0.170	D	1.36	1.48	2.01	0.188
1976	2.03	1.27	2.58	0.169	1.45	1.43	2.07	0.070	D	0.86	1.52	1.31	0.170
1977	1.78	1.34	2.39	0.114	1.27	1.49	1.89	0.129	T	1.60	1.62	2.58	0.234
1978	1.37	1.35	1.85	0.171	1.04	1.55	1.62	0.135	D	1.14	1.67	1.91	0.064
1979	1.96	1.36	2.66	0.230	1.02	1.59	1.62	0.133	T	1.55	1.63	2.53	0.089
1980	2.11	1.31	2.77	0.114	1.27	1.62	2.06	0.105	D	1.88	1.54	2.90	0.096
1981	1.93	1.28	2.48	0.093	1.07	1.64	1.75	0.124	D	0.99	1.51	1.50	0.069
1982	1.52	1.27	1.93	0.109	1.09	1.58	1.73	0.115	S	1.52	1.48	2.26	0.053
1983	1.91	1.20	2.28	0.067	1.45	1.59	2.30	0.161	D	1.40	1.50	2.10	0.097
1984	1.75	1.14	1.99	0.105	1.52	1.57	2.39	0.093	S	0.99	1.47	1.46	0.099
1985	2.01	1.08	2.17	0.132	1.25	1.47	1.83	0.185	T	1.47	1.47	2.16	

Year	BRM02B				BRM03C					DNL02B			
	Ext	Den	Calc	Lum	Ext	Den	Calc	Lum	# lines	Ext	Den	Calc	Lum
1986	2.34	1.09	2.55	0.103	0.76	1.49	1.14	0.175	D	1.19	1.45	1.73	
1987	1.73	1.13	1.96	0.089	1.98	1.55	3.07	0.121	D				
1988	2.29	1.15	2.63	0.085	0.86	1.62	1.40	0.153	T				
1989	1.98	1.11	2.19	0.118	1.63	1.59	2.59	0.122	D				
1990	2.01	1.06	2.13	0.105	1.68	1.54	2.59	0.089	S				
1991	2.04	1.17	2.39	0.084	1.45	1.56	2.26	0.098	S				
1992	2.11	1.09	2.30	0.091	0.69	1.60	1.09	0.119	T				
1993	1.58	1.01	1.59	0.122	1.47	1.68	2.47	0.145	T				

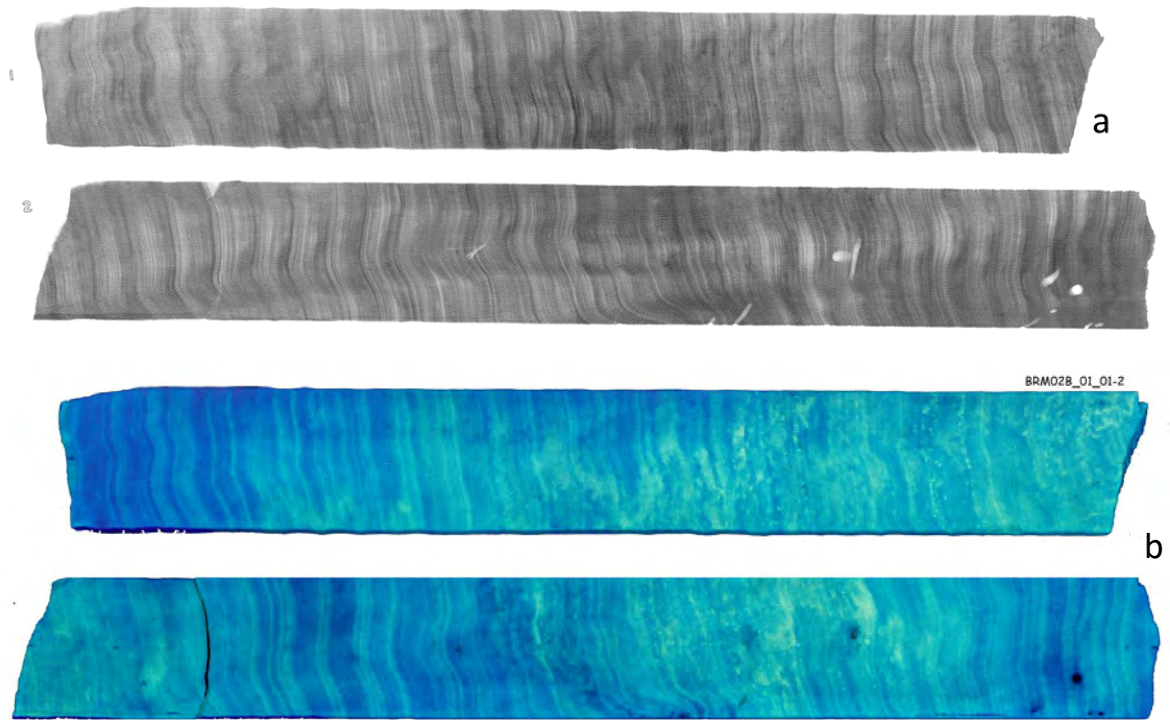


Figure A1: a) X-ray positive prints and b) digitally-enhanced photographs under UV light of coral slices for 2 sections of BMR02B.

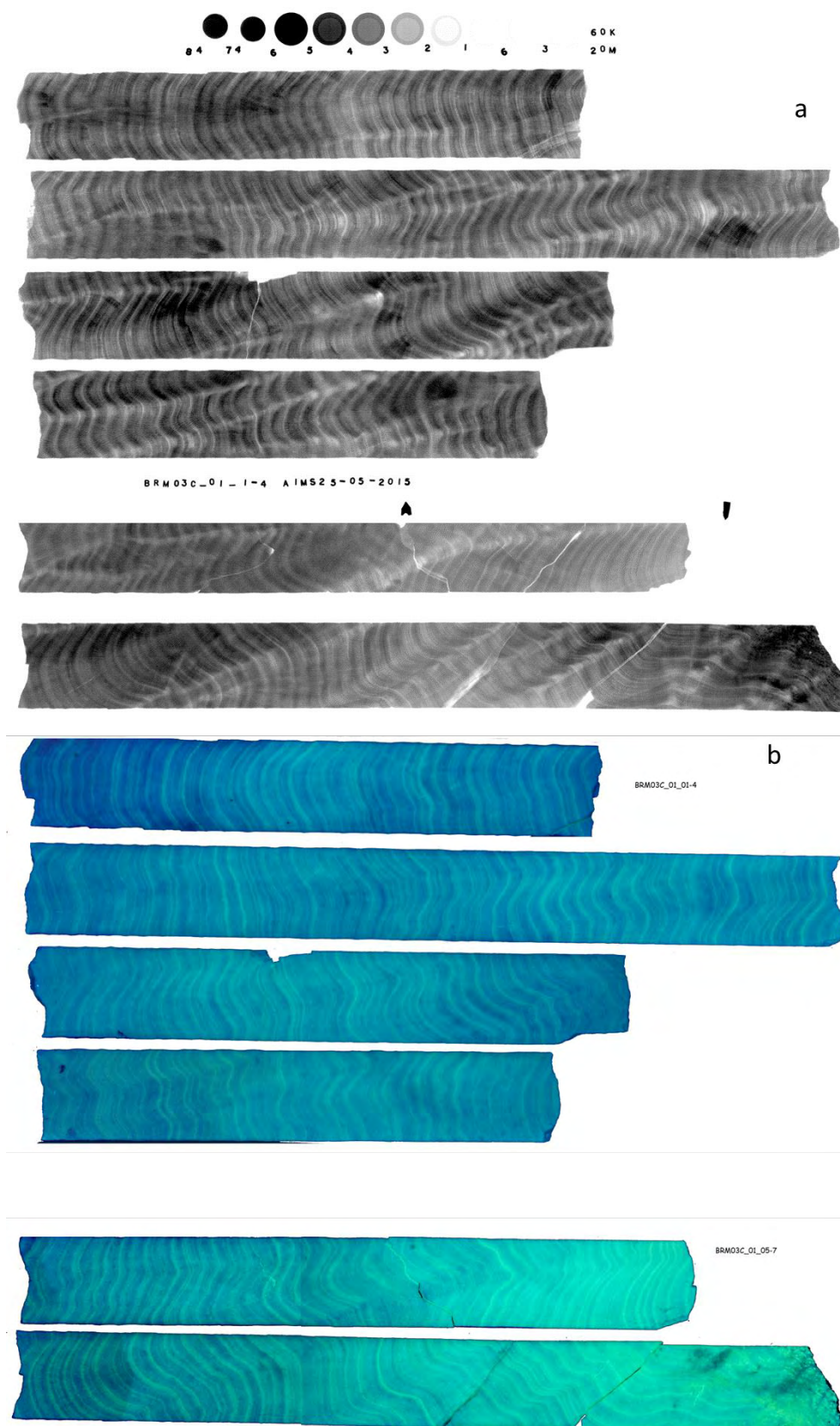


Figure A2: a) X-ray positive prints and b) digitally-enhanced photographs under UV light of coral slices for 6 sections of BMR03C

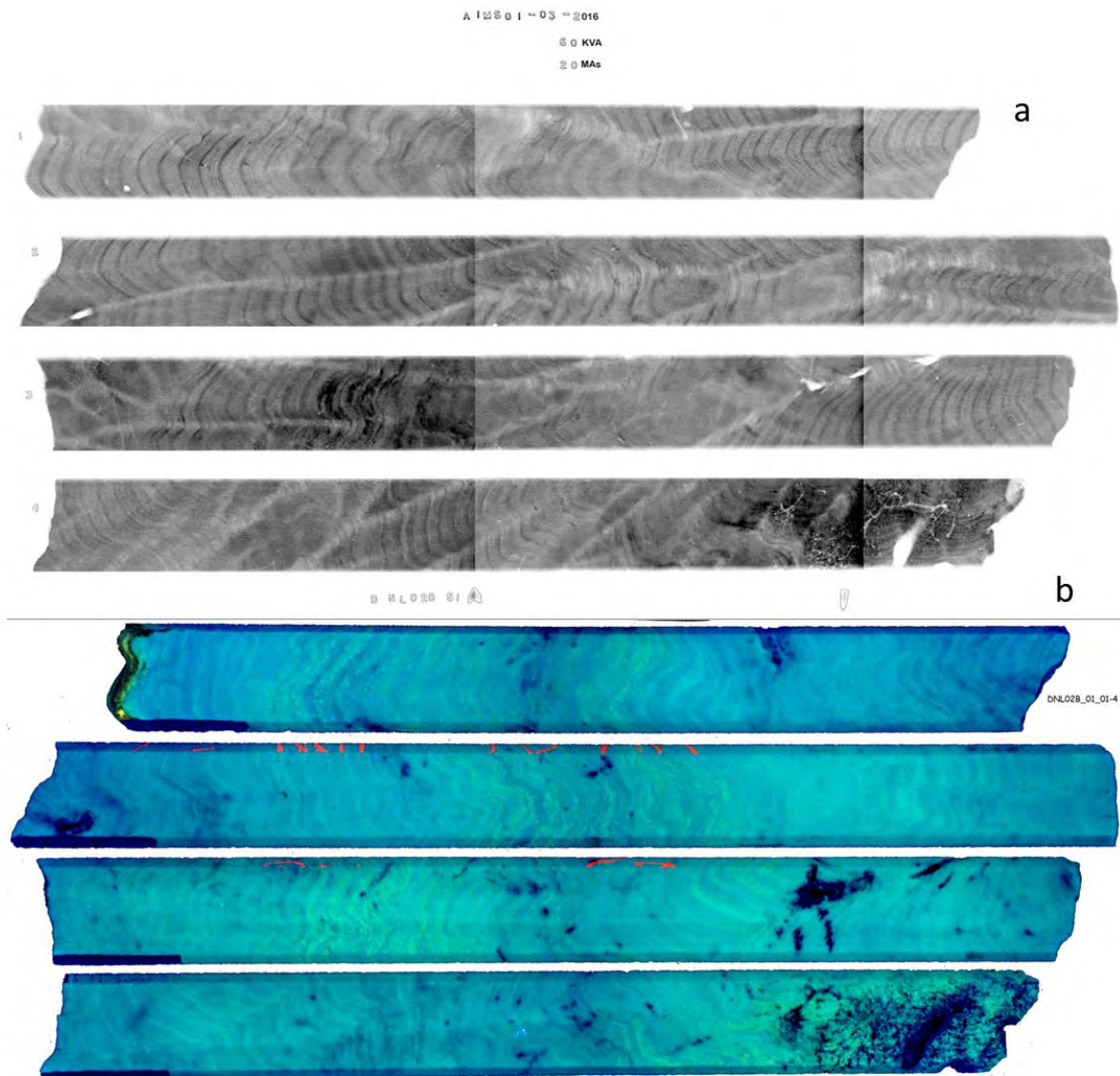


Figure A3: a) X-ray positive prints, and b) digitally-enhanced photographs under UV light of coral slices for 4 sections of DNL02B.

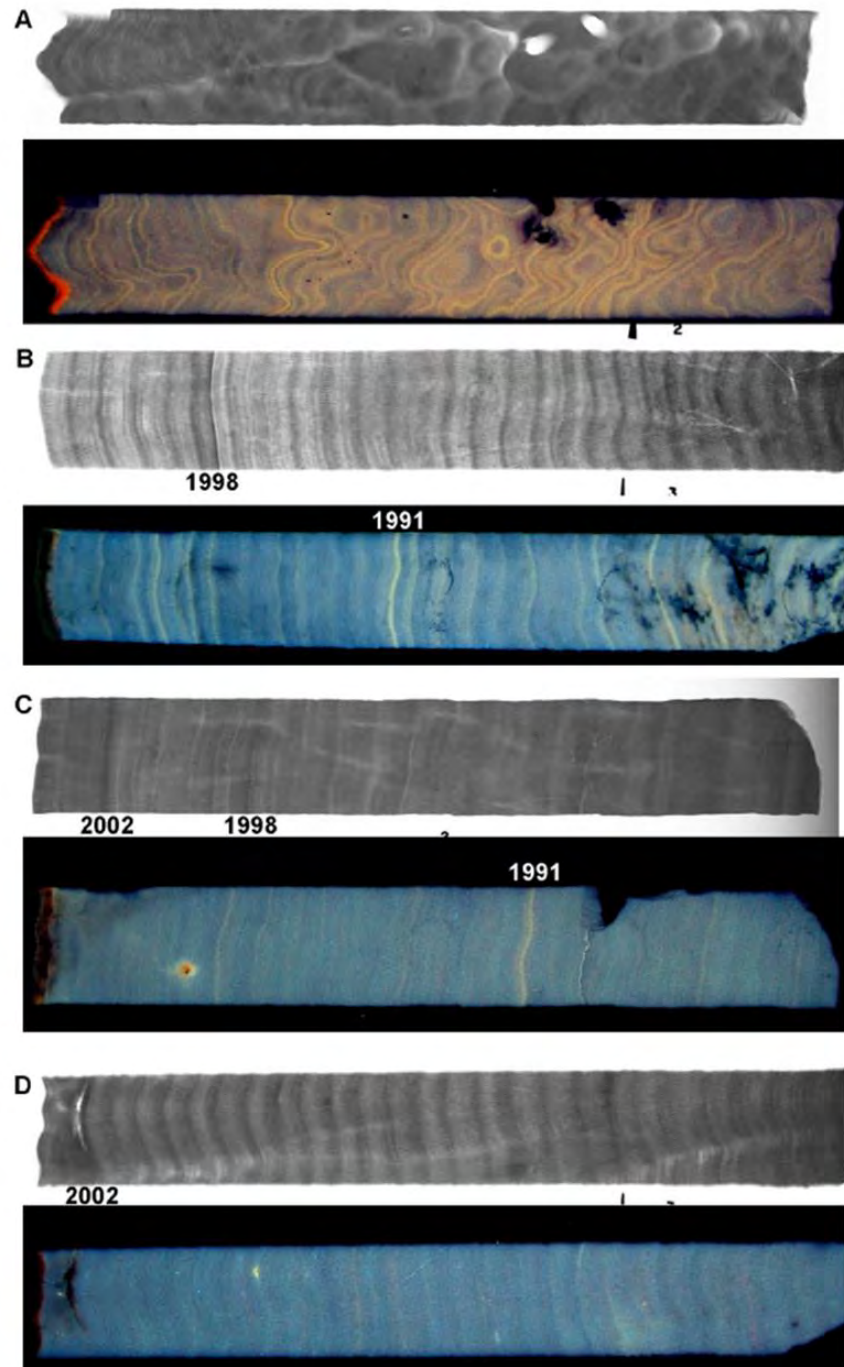


Figure A4: Example positive X-ray prints of Great Barrier Reef coral core slices showing annual density banding and digitally-enhanced photographs under UV light showing luminescent lines and bands.

- A) Nelly Bay illustrating convoluted growth typical of an inshore turbid site and annual luminescent lines;
- B) Pandora illustrating 1998 growth hiatus due to thermal stress and annual luminescent lines typical of reef regularly affected by river flood plumes;
- C) Rib illustrating growth hiatuses in 1998 and 2002 and a bright luminescent line in 1991 associated with a major flood plume reaching this midshelf reef;
- D) Myrmdon illustrating regular density banding typical of an offshore reef with partial mortality in 2002 and faint luminescent bands characteristic of an offshore site never influenced by freshwater flood plumes (from Cantin and Lough, 2014).

