

Measured coral luminescence as a freshwater proxy: comparison with visual indices and a potential age artefact

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Abstract Illuminating slices from massive coral skeletons under ultraviolet light can reveal bright luminescent lines in nearshore corals affected by freshwater river flows. The occurrence and intensity of these lines in long-lived corals can then be used to reconstruct past river flow and rainfall, extending the instrumental records of past tropical climate variability considerably. Earlier studies from the Great Barrier Reef, Australia, have used visual assessments of luminescent line intensity to develop semi-quantitative (though potentially subjective) indices of spatial and temporal variations in freshwater flows. Annual visual assessments and relative coral luminescence intensity (measured by fluorescence spectroscopy) and growth variables are first compared for 89 *Porites* coral colonies from 30 reefs throughout the length and breadth of the GBR. This demonstrates that simple visual assessments can provide useful information, in the absence of quantitative measurements, of this proxy freshwater tracer. The annual range of measured luminescence between the preceding winter minimum and summer maximum, rather than annual average or annual maximum luminescence is shown to be the most robust measure of freshwater flow. Second, from analyses of the coral colony data and over 40-century-long or longer coral core records, attention is drawn to a potential age artefact in annual average and annual maximum measured coral luminescence. These variables show a significant decline through time, similar to the observed decline in average skeletal density. Although the reasons

for this decline are unknown, it could compromise interpretation of long-term variations in freshwater flows and subsequent climatic inferences. This artefact does not appear to affect the annual luminescence range which, it is concluded, is a robust proxy for inter-annual variations in river flow and rainfall.

Keywords Great Barrier Reef · Luminescence · Freshwater · Reconstruction · *Porites* · Palaeoclimate

Introduction

A range of palaeoclimatic tracers contained in long-lived, annually banded, massive coral skeletons make a significant contribution to understanding the nature and causes of past tropical climate variability (Gagan et al. 2000; Corregge 2006; Grottoli and Eakin 2007; Jones et al. 2009; Lough 2010). One of these tracers, the occurrence and intensity of luminescent lines when a coral slice is illuminated by ultraviolet light, can provide information about past river flow and rainfall (Isdale 1984). Since their discovery in inshore corals of the Great Barrier Reef (GBR), Australia, several studies have demonstrated a strong link between luminescence intensity and freshwater river flows and rainfall in adjacent catchments from a range of tropical coral reef locations (Scoffin et al. 1989; Fang and Chou 1992; Neil et al. 1995; Ramsay and Cohen 1997; Kan et al. 2000; Lough et al. 2002; Nyberg 2002; Peng et al. 2002; Kayanne et al. 2006; Deslarzes and Lugo-Fernandez 2007; Jupiter et al. 2008; Grove et al. 2010). Characteristic patterns of luminescent lines in coral slices are also sometimes used to help establish a chronology for other growth and geochemical tracers in massive corals (e.g., Cole et al. 2000; Smithers and Woodroffe 2001; Fleitmann et al.

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2007). There are, however, a few reports where, despite the appearance of bright luminescent lines, there is no clear relationship with adjacent river flow (Scoffin et al. 1989; Moses and Swart 2006) or no immediate source of freshwater flow to the reefs (Tudhope et al. 1996). In a number of locations, several long-term reconstructions of tropical river flow and rainfall have been developed from coral luminescence records (e.g., Smith et al. 1989; Isdale et al. 1998; Hendy et al. 2003; Lough 2007; Nyberg et al. 2007). Such long-term reconstructions of tropical hydroclimate are now being incorporated into multi-proxy reconstructions of larger-scale regional and hemispheric climate indices covering the past several centuries (D'Arrigo et al. 2008; Braganza et al. 2009; Mann et al. 2009a; McGregor et al. 2010).

Initial studies (Boto and Isdale 1985; Susic and Boto 1989; Susic et al. 1991; Fang and Chou 1992) proposed that bright luminescent lines in inshore corals were due to incorporation into the skeleton of terrestrial humic substances during high river flow events. This was questioned by Barnes and Taylor (2001) who suggested that luminescent lines were associated with narrow regions of reduced skeletal density and represented a growth response to reduced salinity. More recent studies (Nyberg 2002; Barnes and Taylor 2005; Grove et al. 2010) do, however, support the initial proposal that the majority of nearshore coral luminescence is due to humic acids.

Various fluorescence spectroscopic techniques have been used to provide quantitative measurements of coral luminescence (Isdale 1984; Milne and Swart 1994; Isdale et al. 1998; Nyberg 2002; Peng et al. 2002; Barnes et al. 2003). These usually involve illuminating the coral slice using fibre optics with excitation light at ~ 360 nm and measuring along the core slice the amount of emitted light at ~ 460 nm, with relative luminescence being calculated as the ratio of the excitation wavelength to emissions wavelength (see review Barnes et al. 2003). The choice of measuring emitted light at ~ 460 nm is based on this being the dominant wavelength for humic acids. Grove et al. (2010) applied spectral luminescence scanning that allowed them to separate the emissions spectra into red, green and blue components. These authors used the green/blue spectral ratio as a measure of luminescence intensity which normalizes for potential affects due to skeletal density and architecture and, they argue, provides a more accurate measurement of luminescence related to river floods than traditional fluorescent spectral techniques which might be affected by skeletal growth characteristics. All these luminescence measurement techniques provide continuous measurements at <1 mm intervals along a core slice. These are then dated and either averaged to provide an annual value or annual peak luminescence, which is then extracted for subsequent comparisons with river flows.

Luminescence in relation to river flows affecting near-shore corals of the GBR has also been determined using simple visual assessment of the occurrence and intensity of luminescent lines. Lough et al. (2002) dated and graded the intensity of luminescence in over 200 small *Porites* colonies on a 4-point scale: 0—no line, 1—faint line, 2—moderately intense line and 3—intense line. Similarly, Hendy et al. (2003) graded luminescence in eight long *Porites* cores on a 5-point scale from negative value indicating absence of a luminescence line, 0—weak line, up to category 3 of very intense line. Lough (2007) applied the grading system to 25 *Porites* coral cores from the GBR using the same categories as Lough et al. (2002), with the addition of category 3.5 for very intense lines. These studies, although based on simple and potentially subjective measures, demonstrated significant relationships between coral luminescence and proximity of the reef to freshwater river flows and similar inter-annual variations in luminescence and river flows. Although using a very simple index, the robustness of the conclusions from these visual assessment studies was enhanced by combing assessments from multiple coral samples (Lough 2004). There have not, however, been any comparisons made between measured luminescence and visual assessments of luminescence intensity. Do both approaches provide equally useful measurements of the occurrence and intensity of luminescent lines and similar relationships with freshwater river flows?

Although there are still relatively few published measured luminescence time series, closer examination shows a tendency in many of these series for luminescence intensity to decrease in magnitude from the older to younger part of the coral sample. A reconstruction of river flow into Florida Bay from 1881–1986 from measured luminescence in a *Solenastrea bournoni* coral core (Smith et al. 1989) found a decrease in flow $\sim 60\%$ from 1881–1939 to 1940–1986. This decrease could, however, be plausibly linked to documented canal construction and consequent regulation of river flows. Isdale et al. (1998) used annual averaged measured coral luminescence in two long *Porites* cores to reconstruct Burdekin River (Queensland, Australia) flow from 1644 to 1980. They noted that one of the coral records showed a significant decreasing trend through time that resulted in a declining trend in the final river flow reconstruction. As only one of the two corals showed this decline, the authors cautioned about this reflecting a real long-term change in average river flow. Ayliffe et al. (2004) measured a range of geochemical tracers, including coral luminescence, over a 20-year period in a *Porites* colony close to the Sepik and Ramu Rivers in northern Papua New Guinea. They remarked upon a declining trend in the measured luminescence series which might suggest a decrease in river

discharge but also noted that no such trends were evident in the other geochemical tracers. Nyberg (2002) presented measured luminescence intensity for a *Montastraea faveolata* core from Mona Island, north-eastern Caribbean, for the period 1900–1995. The author noted a marked downward trend in measured coral luminescence with time, which he suggests was matched by a decline in instrumental rainfall over the same time period, though the latter was not clearly evident from the data presented. Nyberg et al. (2007) combined measured coral luminescence data from four Caribbean coral cores with abundances of the planktonic foraminifera, *Globigerina bulloides*, in a marine sediment core to reconstruct North Atlantic hurricane activity back to 1730. The reconstruction showed a declining trend with time, and the authors concluded that North Atlantic hurricane activity in the 1970s and 1980s was very low when compared to the longer 270-year record. Examination of the series used in the reconstruction (their Fig. 3) suggests that the primary contributor to this reconstructed decrease is the declining trend in measured coral luminescence. The decline in hurricane activity reported by Nyberg et al. (2007) is also not evident in the longer and independently derived estimates of Mann et al. (2009b). Grove et al. (2010) measured luminescence in five *Porites* cores from Madagascar. They reported declining trends in measured luminescence intensity and measured coral skeletal density over the period 1905–2006. Time series of the green/blue spectral ratios, which essentially removes the influence of skeletal density and architecture on measured luminescence, for the same coral cores, did not show declines over time. The authors concluded that the observed declines in coral luminescence intensity were due to declining skeletal density rather than a change in river flows and humic acid delivery to the reef and that this may have affected the interpretation of Nyberg et al. (2007). They suggested that declining skeletal density in massive corals is a modern phenomenon that may reflect a response of coral growth to current rapid environmental changes affecting coral reefs (Cooper et al. 2008; De'ath et al. 2009; Tanzil et al. 2009; Cantin et al. 2010; Manzello 2010). A decline in skeletal density through time may, however, be the result of an age effect on coral growth characteristics (Lough 2008). On much longer timescales, Klein et al. (1990) compared measured luminescence in late Quaternary fossil and modern *Porites* coral from the southern Sinai Desert and Red Sea. The luminescence intensity was higher in the fossil corals, and they inferred this represented much wetter summer rainfall conditions in this region in the late Quaternary compared to present climate. The question, therefore, arises as to whether the inferences concerning recent reductions in river flow/hurricane activity made from measured coral luminescence intensities are valid. Are

declines in measured luminescence intensity some sort of age artefact that might be related to an apparent age effect on skeletal density?

Using annual coral growth and luminescence variables measured in multiple *Porites* coral colony and long coral core samples from the GBR, Australia, this study addresses the following questions:

- Are simple visual assessments of luminescence line intensity comparable to measured luminescence indices?
- Which measured luminescence indices are most strongly related to river flows?
- Are there any relationships between average coral growth characteristics and luminescence indices?
- Are there growth artefacts in measured coral luminescence?

Materials and methods

Coral samples

Coral colonies

Visual luminescence indices, luminescence and annual growth (extension, density and calcification) were measured in 89 massive coral colonies from the GBR. These colonies are a subset of the 232 colonies analysed by Lough et al. (2002) and were selected on the basis of clear annual density banding for three colonies per reef site (with the exception of Ashmore Reef for which only two colonies met the criteria). Small (0.3–0.5 m in height) massive *Porites* were collected, in 1988, 1989, 1990, 1992 and 2000, from similar shallow-water environments from 30 reefs on the GBR (see Lough et al. 1999). The reef sites span 11° of latitude from the northern to the southern GBR and from coastal (0 km) to offshore (176 km) sites. Six of the reefs were offshore (17 colonies), 8 were midshelf (24 colonies) and 16 reefs were inshore (48 colonies) (Table 1; Lough et al. 2002).

Coral cores

The potential for artefacts to affect interpretation of coral luminescence measurements was tested over longer timescales using annual measurements of growth and luminescence variables from AIMS' Coral Core Database. These were available for growth variables from 43 cores and for luminescence variables from 37 cores—cores were selected on the basis that they contained at least 100 years of data. The records started at various times from the late nineteenth century with the longest starting in the sixteenth century (Table 2).

Table 1 Details of coral colonies used in the analyses

Reef (AIMS bommie ID)	Latitude °S	Longitude °E	Distance from land km	% distance across shelf	Average water depth m	Inshore, midshelf or offshore
Ashmore (04, 08)	10.3	144.5	176	100	201	Off
Lagoon (02, 08, 13)	12.4	143.7	42	100	30	Off
Eel (03, 07, 08)	12.5	143.5	14	33	27	Mid
Portland Roads (02, 03, 06)	12.6	143.4	0	0	1	In
Rocky Is (05, 06, 07)	12.6	143.4	1	2	2	In
Night Is (04, 10, 12)	13.2	143.6	6	15	2	In
13–055 (09, 10, 14)	13.3	143.8	19	48	13	Mid
13–050 (04, 06, 10)	13.3	143.9	40	100	27	Off
Tydeman (02, 03, 05)	14.0	144.5	20	42	22	Off
Pipon (01, 02, 05)	14.1	144.5	6	11	16	In
Flinders Is (02, 05, 07)	14.2	144.3	13	23	10	In
Watson Is (05, 07, 11)	14.5	144.9	16	32	10	In
S Petherbridge (02, 05, 06)	14.7	145.1	8	15	3	In
Two Isles (02, 05, 06)	15.0	145.4	10	26	22	In
Boulder (01, 02, 03)	15.4	145.4	14	26	20	Mid
E Hope (01, 02, 09)	15.7	145.5	10	21	18	In
Undine (01, 03, 05)	16.1	145.6	19	45	29	Mid
Snapper (01, 02, 05)	16.3	145.5	2	4	12	In
Batt (02, 06, 09)	16.4	145.7	28	41	27	Mid
Double Is (02, 04, 08)	16.7	145.7	1	2	2	In
Stephens Is (03, 04, 11)	17.7	146.2	6	12	6	In
Bedarra Is (02, 11, 12)	18.0	146.1	6	9	8	In
Myrmidon (50, 51, 52)	18.3	147.4	110	100	50	Off
Rib (48, 53, 54)	18.5	146.7	56	51	33	Mid
Pandora (47, 48, 53)	18.8	146.4	16	15	8	In
Shaw Is (05, 10, 12)	20.5	149.1	18	10	22	In
20–200 (05, 09, 12)	20.5	150.6	174	99	44	Off
Credlin (03, 05, 10)	20.5	149.9	106	61	36	Mid
21–141 (11, 12, 14)	21.5	151.2	145	68	60	Mid
Middle Percy (02, 03, 10)	21.7	150.3	80	38	18	In

Three colonies were analysed for all reefs with the exception of Ashmore Reef for which only 2 colonies were used

Coral luminescence and growth data

Coral growth variables

Coral skeletal density was measured at 0.25-mm intervals along the central, most vertical, growth axis of each colony or core slice using gamma densitometry and a 4-mm-diameter gamma ray beam (Chalker and Barnes 1990; Lough and Barnes 1990). Working back from the date of collection of the coral sample and assuming that the high density band forms in summer on the GBR, the distance vs. absolute density trace was dated and three annual coral growth variables extracted (see Lough et al. 1999; Lough and Barnes 2000):

- Average skeletal density (g cm^{-3})
- Linear extension, measured as linear distance between adjacent density minima (cm year^{-1})

- Calcification, the product of annual linear extension and average annual skeletal density ($\text{g cm}^{-2} \text{year}^{-1}$)

Coral luminescence variables

Coral luminescence intensity (excitation k (nm)/emission k (nm) = 390/490) was measured at 0.25-mm intervals, using optical luminometry along the same track as density and during the same machine run (Barnes et al. 2003). Luminescence and reflectance were measured against background values (to allow for possible drift within and between sample runs) at the start and end of each run.

Working back from the date of collection of the coral sample and assuming that peak luminescence occurs during the wet summer season and minimum luminescence in the

Table 2 Details of coral cores used in the analyses

Reef	AIMS Core ID	Latitude °S	Longitude °E	Growth and/or luminescence	Start Year	End Year	Inshore, midshelf or offshore
Darnley	DNL02B	9.58	143.77	G	1812	1986	Off
Red Wallis	RWI01B	10.83	142.17	G & L	1857	1985	Off
Pascoe	PCO01B	12.52	143.27	G & L	1829	1985	In
Jeannie	JNE01A	14.67	144.93	G & L	1749	1986	In
Agincourt	AGC01B	15.90	145.82	G & L	1781	1988	Off
Normanby	NOR01B	17.20	146.07	G & L	1872	1984	In
Flinders	FLI01A	17.73	148.43	G & L	1700	1991	Off
Flinders	FLI02A	17.73	148.43	G & L	1699	1991	Off
Kurrimine	KMN02B	17.78	146.13	G & L	1783	1980	In
Dunk	DUN02A	17.95	146.17	G & L	1867	1988	In
Coombe	COO01E	18.03	146.18	G & L	1843	1966	In
Otter	OTT01A	18.05	146.58	G	1811	1988	Mid
Brook	BRO01A	18.15	146.28	G & L	1786	1987	In
Britomart	BRT01A	18.23	146.73	G	1621	1983	Mid
Britomart	BRT01B	18.23	146.73	G	1572	1987	Mid
Myrmidon	MYR01C	18.27	147.38	G & L	1667	1983	Off
Kelso	KEL02AS2	18.42	146.98	G	1861	2001	Mid
Kelso	KEL02AS3	18.42	146.98	G & L	1865	2001	Mid
Kelso	KEI02B	18.42	146.98	G & L	1900	2001	Mid
Rib	RIB01A	18.48	147.88	L	1881	1982	Mid
Rib	RIB02A	18.48	147.88	G & L	1860	2000	Mid
Rib	RIB02B	18.48	147.88	G & L	1844	2000	Mid
Rib	RIB03B	18.48	147.88	G & L	1858	2001	Mid
Great Palm	GPI02A	18.68	146.58	G & L	1880	1985	In
Lodestone	LOD01A	18.70	147.10	G	1753	1984	Mid
Wheeler	WHE02B	18.80	147.53	G	1830	1984	Mid
Pandora	PAN04B	18.82	146.43	G	1864	1983	In
Havannah	HAV01A	18.85	146.55	G & L	1639	1988	In
Acheron	ACH01A	18.90	146.65	L	1875	1984	In
Magnetic	MAG01D	19.15	146.87	G & L	1813	1986	In
Hook	HKO01B	20.07	148.95	G & L	1660	1985	In
Stonehaven	SNH01A	20.10	148.90	G & L	1819	1992	In
North Molle	NMI01B	20.23	148.80	G & L	1881	1984	In
Cid Harbour	CID01A	20.27	148.93	G & L	1824	1991	In
South Molle	SMI01C	20.27	148.83	G & L	1853	1984	In
Lupton	LUP01C	20.28	149.12	G & L	1825	1983	In
Scawfell	SCF01A	20.88	149.60	G & L	1818	1986	Mid
Sanctuary	SAN01A	22.07	152.67	G & L	1684	1984	Off
Abraham	ABR01A	22.10	152.50	G	1645	1985	Off
Abraham	ABR01H	22.10	152.50	G & L	1606	2001	Off
Sweetlip	SWL01A	22.23	152.75	G & L	1891	2001	Off
Sweetlip	SWL02A	22.23	152.75	G & L	1837	2001	Off
Sweetlip	SWL03A	22.23	152.75	G & L	1874	2001	Off
Sweetlip	SWL03B	22.23	152.75	G & L	1806	2001	Off
Humpy	HMP01A	23.20	150.97	L	1823	1996	In
Humpy	HMP01B	23.20	150.97	L	1684	1995	In
Masthead	MAS01C	23.55	151.73	G	1866	1986	Mid

dry winter season, the following annual luminescence variables were extracted:

- Maximum luminescence
- Minimum luminescence
- Average luminescence, average between adjacent luminescence minima
- Luminescence range, measured as the difference between maximum luminescence (summer) and the preceding minimum luminescence (winter)
- Linear extension rate, measured as linear distance between adjacent luminescent minima (cm year^{-1})

In addition, for each coral slice and measured luminescence/density track, a visual luminescence intensity was assigned to each annual luminescent line. The scale ranged from 0 (no luminescent line) to 3 (intense luminescent line) (see Lough et al. 2002; Lough 2007).

Environmental variables

Annual water year (October–September) river flow volumes were used for six major rivers affecting nearshore reefs of the GBR: Barron, Herbert, South Johnstone, Burdekin, Pioneer and Fitzroy rivers. Data were obtained from the Queensland Government Department of Environment and Resource Management (http://www.derm.qld.gov.au/water/monitoring/current_data/index.php).

The movement of freshwater flood plumes into the GBR is complex and influenced by both the Coriolis force, which tends to force the plumes to spread northwards, and local wind conditions (King et al. 2001). The width of the GBR also varies considerably along its length and, as a consequence, the simple linear distance to the mainland is not the best measure of the extent of terrestrial influence on a particular coral reef. This distance was, therefore, expressed as the percentage of the total width of the shelf at the latitude of each reef. The average water depth (m) between each reef and the nearest point on the mainland was determined from the bathymetry data model for the GBR (Lewis 2001; see Lough et al. 2002 for further details).

Analyses

Comparisons between visual and measured luminescence and growth variables

For the 89 coral colonies, comparisons were based on the period 1977–1985, common to all coral samples. Annual rainfall and river flow for this short 9-year period encompassed both relatively wet (e.g. 1979) and relatively dry (e.g. 1983) years (see Figure 1 in Lough 2007). Average statistics and correlations and regressions between different variables were calculated. Annual luminescence indices (average,

maximum and range) for 13 of the inshore reefs with more than 15 years of record, averaged by reef, were correlated with annual water year flows for the river closest to each reef.

Identification of possible age artefact in measured luminescence colonies

For 83 of the colonies with 15 or more years of annual data, average luminescence, luminescence range, average density and linear extension were standardized by dividing each series by the respective long-term mean. This procedure allowed for different mean values of the individual colonies. The 83 series were then averaged, expressed as anomalies from the overall mean of 1.0 and tested for significant linear trends for a) 1964–1988, the 25-year period with data from at least 50% up to 100% of the colonies, and b) years 1–25 in which the first year of each series (which ranged from 1931 to 1975) was set to year 1 regardless of the actual start year (cf. Lough 2008). Note, when dating and extracting growth and luminescence variables from coral colonies, typically the earliest 5–10 years of growth from the oldest part of the colony or core are excluded due to unclear density banding, so the first dated year does not coincide with the first year of coral growth.

Identification of possible age artefact in measured luminescence cores

To test for possible effects over decadal to centennial timescales, the annual growth and luminescence variables from selected long cores were first expressed as standardized anomalies from the respective mean and SD of the period 1891–1980, common to all the cores. This standardization allowed for differences between corals in average growth rates and their variability. The first 100 years of each standardized record (regardless of actual start year) were then set to years 1 to 100. The different annual coral growth and luminescence variables were then averaged for years 1–10, 11–20...91–100. If there was no effect of age on the variables, this procedure should effectively randomize anomalies and the 10-year averages would be expected to vary close to zero. Note, as with the coral colonies, the earliest dated year does not coincide with the first year of coral growth.

Results

Average statistics and relationships between variables: colonies

Average growth and luminescence variables for the 30 reef sites are provided in Table 3. When averaged by reef

Table 3 Average growth and luminescence indices for 30 coral reef sites for, 1977–1985 ±SD ($n = 27$ except for Ashmore Reef, $n = 16$)

Reef	Extension cm year ⁻¹	Density g cm ⁻³	Calcification g cm ⁻² year ⁻¹	Extension lum cm year ⁻¹	Mx lum	Mn lum	Average lum	Range lum	Visual lum
Ashmore	0.94 ± 0.15	1.30 ± 0.04	1.22 ± 0.19	0.98 ± 0.24	0.70 ± 0.14	0.59 ± 0.11	0.63 ± 0.11	0.11 ± 0.11	0.00
Lagoon	1.17 ± 0.23	1.50 ± 0.09	1.74 ± 0.34	1.13 ± 0.44	0.62 ± 0.08	0.54 ± 0.07	0.57 ± 0.06	0.08 ± 0.05	0.33 ± 0.47
Eel	1.35 ± 0.26	1.29 ± 0.09	1.72 ± 0.34	1.37 ± 0.39	0.87 ± 0.07	0.70 ± 0.05	0.76 ± 0.04	0.16 ± 0.08	1.07 ± 1.00
Portland Roads	1.67 ± 0.41	1.19 ± 0.12	2.00 ± 0.47	1.66 ± 0.46	1.01 ± 0.10	0.83 ± 0.10	0.90 ± 0.09	0.19 ± 0.07	1.85 ± 0.78
Rocky Is	1.52 ± 0.41	1.27 ± 0.09	1.93 ± 0.55	1.55 ± 0.30	1.06 ± 0.10	0.78 ± 0.10	0.90 ± 0.09	0.28 ± 0.08	1.85 ± 0.75
Night Is	1.26 ± 0.40	1.30 ± 0.10	1.61 ± 0.46	1.28 ± 0.55	1.07 ± 0.28	0.85 ± 0.24	0.93 ± 0.25	0.22 ± 0.10	1.72 ± 0.58
13–055	1.01 ± 0.23	1.27 ± 0.12	1.28 ± 0.28	0.95 ± 0.35	0.75 ± 0.08	0.64 ± 0.09	0.68 ± 0.08	0.11 ± 0.05	0.94 ± 0.97
13–050	1.34 ± 0.29	1.34 ± 0.11	1.78 ± 0.37	1.25 ± 0.29	0.69 ± 0.07	0.59 ± 0.06	0.62 ± 0.05	0.11 ± 0.07	0.56 ± 0.51
Tydeman	1.17 ± 0.20	1.29 ± 0.09	1.50 ± 0.22	1.12 ± 0.32	0.73 ± 0.11	0.58 ± 0.06	0.64 ± 0.06	0.14 ± 0.08	1.22 ± 1.17
Pipon	1.41 ± 0.32	1.27 ± 0.07	1.79 ± 0.44	1.50 ± 0.32	0.82 ± 0.13	0.57 ± 0.09	0.65 ± 0.08	0.26 ± 0.13	2.04 ± 0.74
Flinders Is	1.32 ± 0.32	1.26 ± 0.12	1.67 ± 0.50	1.31 ± 0.21	0.86 ± 0.14	0.59 ± 0.07	0.70 ± 0.07	0.26 ± 0.13	2.15 ± 0.77
Watson Is	1.58 ± 0.42	1.20 ± 0.08	1.88 ± 0.44	1.51 ± 0.47	0.81 ± 0.13	0.61 ± 0.11	0.69 ± 0.12	0.19 ± 0.07	1.89 ± 0.64
S Petherbridge	1.34 ± 0.26	1.21 ± 0.10	1.61 ± 0.29	1.32 ± 0.40	0.89 ± 0.09	0.68 ± 0.06	0.76 ± 0.06	0.21 ± 0.09	2.00 ± 0.73
Two Isles	1.33 ± 0.37	1.24 ± 0.09	1.63 ± 0.38	1.26 ± 0.31	0.63 ± 0.09	0.44 ± 0.06	0.52 ± 0.05	0.19 ± 0.09	1.72 ± 0.83
Boulder	1.22 ± 0.46	1.26 ± 0.11	1.55 ± 0.51	1.18 ± 0.49	0.80 ± 0.09	0.67 ± 0.09	0.73 ± 0.08	0.13 ± 0.07	0.85 ± 0.66
E Hope	1.54 ± 0.29	1.19 ± 0.12	1.83 ± 0.35	1.59 ± 0.47	0.84 ± 0.10	0.62 ± 0.08	0.71 ± 0.07	0.22 ± 0.09	1.82 ± 0.74
Undine	1.17 ± 0.27	1.27 ± 0.09	1.48 ± 0.34	1.17 ± 0.27	0.70 ± 0.06	0.55 ± 0.06	0.61 ± 0.04	0.15 ± 0.06	0.70 ± 0.99
Snapper	1.85 ± 0.37	1.19 ± 0.08	2.20 ± 0.45	1.79 ± 0.44	0.99 ± 0.12	0.66 ± 0.05	0.77 ± 0.06	0.29 ± 0.09	2.00 ± 0.71
Batt	1.20 ± 0.42	1.39 ± 0.06	1.67 ± 0.56	1.21 ± 0.41	0.67 ± 0.09	0.50 ± 0.07	0.58 ± 0.07	0.16 ± 0.07	0.85 ± 0.82
Double Is	1.61 ± 0.48	1.13 ± 0.08	1.80 ± 0.53	1.73 ± 0.54	1.06 ± 0.11	0.72 ± 0.06	0.83 ± 0.05	0.34 ± 0.11	1.93 ± 0.78
Stephens Is	1.55 ± 0.52	1.06 ± 0.07	1.63 ± 0.57	1.49 ± 0.33	1.11 ± 0.13	0.76 ± 0.06	0.88 ± 0.07	0.34 ± 0.11	2.12 ± 0.77
Bedarra Is	1.37 ± 0.42	1.22 ± 0.07	1.66 ± 0.48	1.40 ± 0.37	1.22 ± 0.24	0.79 ± 0.12	0.95 ± 0.15	0.43 ± 0.17	1.85 ± 0.82
Myrmidon	0.93 ± 0.37	1.42 ± 0.11	1.29 ± 0.44	0.91 ± 0.36	0.57 ± 0.10	0.51 ± 0.09	0.54 ± 0.09	0.06 ± 0.04	0.00
Rib	1.22 ± 0.34	1.33 ± 0.07	1.61 ± 0.41	1.21 ± 0.34	0.65 ± 0.08	0.55 ± 0.06	0.59 ± 0.06	0.10 ± 0.04	0.37 ± 0.57
Pandora	1.63 ± 0.52	1.12 ± 0.09	1.91 ± 0.63	1.58 ± 0.48	0.82 ± 0.19	0.56 ± 0.12	0.65 ± 0.13	0.26 ± 0.14	1.93 ± 0.87
Shaw Is	0.75 ± 0.25	1.39 ± 0.07	1.03 ± 0.33	0.78 ± 0.25	0.86 ± 0.16	0.70 ± 0.13	0.77 ± 0.14	0.16 ± 0.06	1.31 ± 0.48
20–200	0.91 ± 0.36	1.38 ± 0.09	1.23 ± 0.43	0.92 ± 0.38	0.60 ± 0.07	0.48 ± 0.04	0.54 ± 0.05	0.12 ± 0.05	0.00
Credlin	0.92 ± 0.23	1.18 ± 0.12	1.09 ± 0.30	0.97 ± 0.32	0.72 ± 0.05	0.61 ± 0.05	0.66 ± 0.05	0.12 ± 0.04	0.00
21–141	0.92 ± 0.27	1.38 ± 0.15	1.26 ± 0.40	0.91 ± 0.27	0.66 ± 0.11	0.53 ± 0.09	0.59 ± 0.09	0.13 ± 0.06	0.00
Middle Percy	0.96 ± 0.22	1.40 ± 0.10	1.34 ± 0.29	0.93 ± 0.24	0.77 ± 0.09	0.63 ± 0.07	0.69 ± 0.06	0.15 ± 0.07	1.57 ± 0.66

Table 4 Average growth and luminescence indices (\pm SD) for inshore, midshelf and offshore reef sites

	Inshore	Midshelf	Offshore
% distance across shelf	14.6 \pm 10.8	46.6 \pm 13.2	89.6 \pm 22.7
Average water depth m	10.1 \pm 7.1	30.6 \pm 13.3	53.5 \pm 56.4
Extension cm year ⁻¹	1.42 \pm 0.32	1.12 \pm 0.20	1.08 \pm 0.26
Density g cm ⁻³	1.23 \pm 0.12	1.30 \pm 0.12	1.37 \pm 0.11
Calcification g cm ⁻² year ⁻¹	1.73 \pm 0.35	1.45 \pm 0.24	1.47 \pm 0.32
Extension lum cm year ⁻¹	1.42 \pm 0.33	1.13 \pm 0.19	1.06 \pm 0.23
Mx lum	0.93 \pm 0.19	0.73 \pm 0.09	0.65 \pm 0.09
Mn lum	0.68 \pm 0.14	0.59 \pm 0.09	0.54 \pm 0.07
Av lum	0.77 \pm 0.15	0.65 \pm 0.08	0.59 \pm 0.07
Range	0.25 \pm 0.09	0.13 \pm 0.03	0.10 \pm 0.03
Visual lum	1.86 \pm 0.25	0.60 \pm 0.47	0.37 \pm 0.47
# corals	48	24	17

location across the shelf (Table 4), these show previously reported growth and luminescence relationships (e.g., Risk and Sammarco 1991; Lough and Barnes 2000; Lough et al. 2002) with proximity to terrestrial influence. Linear extension (which shows very similar average values when measured either from skeletal density or luminescence) decreased from inshore to offshore whilst skeletal density increased across the same gradient and calcification rates were highest in inshore reefs. The five luminescence indices all showed highest values in inshore reefs and lowest values in offshore reefs.

There were several significant correlations between growth and luminescence variables for the 30 reefs (Table 5). All growth and luminescence variables were, however, significantly correlated with the relative position

of the reef across the shelf. Partial correlations were, therefore, calculated, allowing for the effects of % distance across the shelf (Table 6). Relationships between *Porites* annual growth variables were similar to those described previously (Lough and Barnes 2000; Lough 2008) with density and extension being inversely related and extension more strongly correlated with calcification rate than density. Linear extension measured either between density minima or luminescence minima were strongly correlated ($r = 0.98$). Maximum, minimum and average luminescence were also strongly correlated (r -values > 0.8) but only maximum luminescence was significantly correlated with luminescence range. There was a significant correlation (0.78) and partial correlation (0.42) between the luminescence range and the visual luminescence index. Although maximum, minimum and average luminescence were significantly correlated with the visual luminescence index, these were not significant for partial correlations, allowing for the relative distance across the shelf, i.e., it is the amplitude of the luminescence (range) that is most clearly captured by the visual assessment technique.

Although there was a significant linear relationship between the visual luminescence index and luminescence range (R^2 62%), the relationship was better described by a polynomial fit (R^2 80%) (Fig. 1). This indicated that measured luminescence range did not reach zero values and that the visual index reached a plateau ~ 2.0 , whilst the measured ranges continued to increase.

Lough et al. (2002) show that the visual luminescence indices were significantly inversely related to relative distance across the shelf (as well as average water depth between the reef and land). This was again evident for the data presented here (Fig. 2a) and for the luminescence range (Fig. 2b).

Table 5 Correlations between coral growth, luminescence and environmental variables by reef ($n = 30$)

	Latitude	Longitude	% shelf	Depth	Ext	Density	Calc	Ext-lum	Mx lum	Mn lum	Av lum	Range	Visual
Latitude	1.00												
Longitude	0.93	1.00											
% shelf	0.03	0.24	1.00										
Depth	-0.15	0.13	0.62	1.00									
Ext	-0.35	-0.55	-0.62	-0.47	1.00								
Density	0.10	0.23	0.63	0.29	-0.67	1.00							
Calc	-0.43	-0.61	-0.49	-0.45	0.95	-0.41	1.00						
Ext-lum	-0.35	-0.54	-0.65	-0.45	0.98	-0.69	0.92	1.00					
Mx lum	-0.14	-0.31	-0.77	-0.43	0.58	-0.62	0.44	0.63	1.00				
Mn lum	-0.22	-0.32	-0.61	-0.34	0.38	-0.43	0.27	0.41	0.90	1.00			
Av lum	-0.19	-0.32	-0.71	-0.39	0.48	-0.53	0.36	0.52	0.97	0.98	1.00		
Range	0.00	-0.19	-0.74	-0.42	0.66	-0.67	0.53	0.71	0.85	0.54	0.70	1.00	
Visual	-0.19	-0.40	-0.87	-0.61	0.78	-0.61	0.64	0.74	0.73	0.51	0.63	0.78	1.00

Coefficients significant at 5% level in bold

Table 6 Partial correlations between coral growth, luminescence and environmental variables by reef, allowing for the effects of % distance across shelf ($n = 30$)

	Latitude	Longitude	Depth	Ext	Density	Calc	Ext-lum	Mx lum	Mn lum	Av lum	Range	Visual
Latitude	1.00											
Longitude	0.95	1.00										
Depth	-0.21	-0.03	1.00									
Ext	-0.43	-0.52	-0.14	1.00								
Density	0.10	0.10	-0.17	-0.47	1.00							
Calc	-0.48	-0.59	-0.22	0.94	-0.15	1.00						
Ext—lum	-0.43	-0.52	-0.08	0.98	-0.47	0.91	1.00					
Mx lum	-0.19	-0.19	0.09	0.21	-0.27	0.12	0.26	1.00				
Mn lum	-0.26	-0.22	0.06	0.00	-0.08	-0.04	0.02	0.84	1.00			
Av lum	-0.24	-0.22	0.08	0.07	-0.15	0.02	0.11	0.94	0.97	1.00		
Range	0.04	-0.02	0.07	0.39	-0.38	0.28	0.45	0.66	0.16	0.37	1.00	
Visual	-0.34	-0.39	-0.19	0.50	-0.16	0.49	0.44	0.19	-0.06	0.03	0.42	1.00

Coefficients significant at 5% level in bold

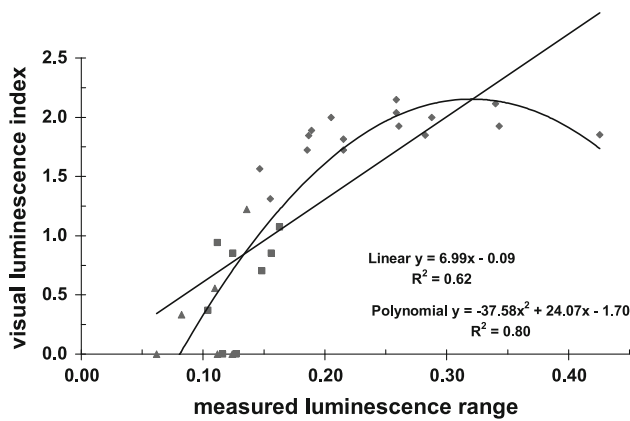


Fig. 1 Relationship between average visual luminescence indices and average measured luminescence range for 30 reefs. *Diamonds* are inshore reefs, *squares* are midshelf reefs and *triangles* are offshore reefs. Also shown are linear and polynomial regressions

Correlations between reef average luminescence indices and adjacent river flows for 13 inshore reefs showed that for 9 reefs (69%), the maximum significant correlation was with the luminescence range and for 4 reefs (31%), the maximum significant correlation was with maximum luminescence. Although significant correlations were found between river flow and average annual luminescence, these were always of lower magnitude than the correlations with luminescence range and maximum annual luminescence.

Potential long-term artefact in average luminescence and density

Coral colonies

When standardized anomalies were averaged across 83 colonies and plotted against calendar year and years 1 to 25,

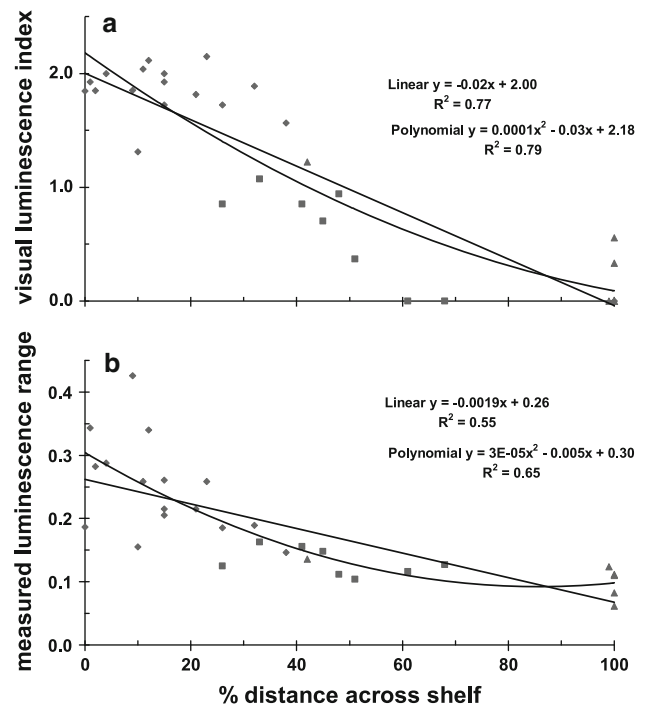


Fig. 2 Relationships between % distance across shelf and **a** visual luminescence index and **b** measured luminescence range for 30 reef sites. *Diamonds* are inshore reefs, *squares* are midshelf reefs and *triangles* are offshore reefs. Also shown are linear and polynomial regressions

regardless of start year, clear differences were evident for average luminescence and average skeletal density (Fig. 3). Significant decreasing linear trends were found for average luminescence (Fig. 3a) and average skeletal density (Fig. 3c). Average luminescence range (Fig. 3b) and average linear extension (Fig. 3d) did not show significant linear trends with time. In addition, the magnitude and

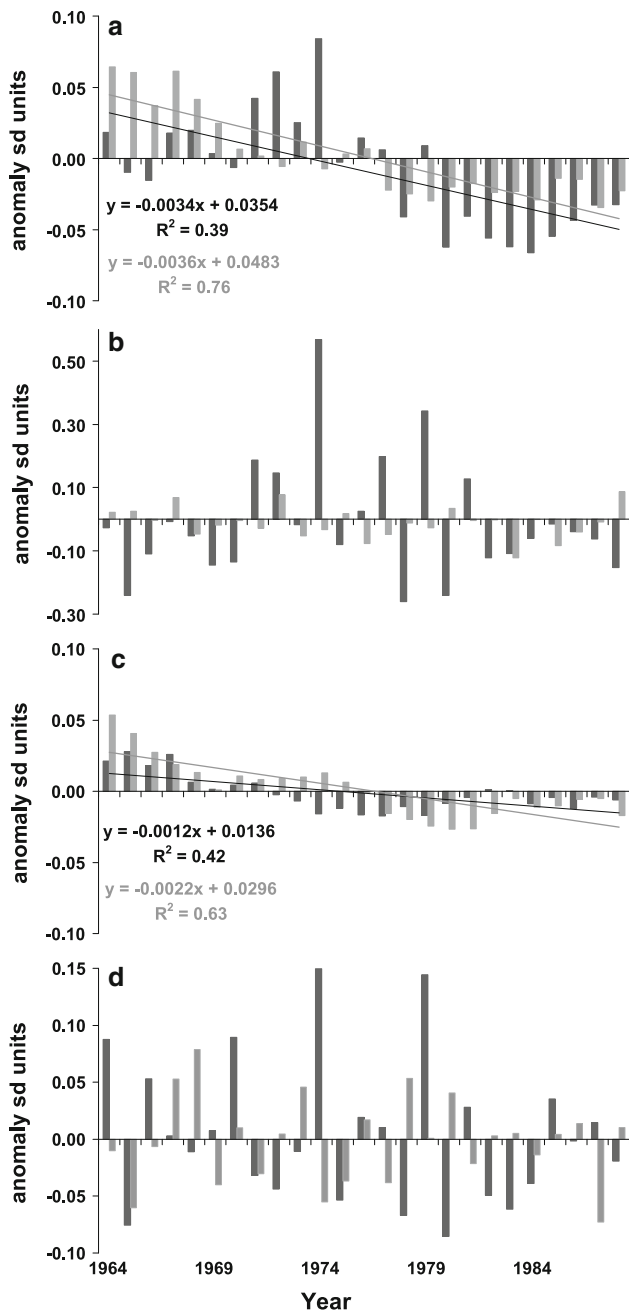


Fig. 3 Standardized anomalies averaged for 83 colonies for 1964–1988 (*black bars*) and years 1–25 (*grey bars*) for **a** average luminescence, **b** luminescence range, **c** skeletal density and **d** linear extension. Significant (at 5% level) linear regressions are also shown

percentage variance explained by the declining trend increased for average luminescence and skeletal density from lower values based on calendar years to higher values when all series were set to the same start year. The R^2 value increased from 39 to 76% for average luminescence and from 42 to 63% for average skeletal density. The same pattern of linear trends, as found for average luminescence, were evident when maximum and minimum luminescence were examined separately (not shown).

Coral cores

First, examination of 34 individual coral series over 100 years in length, and on a calendar year basis, showed that 77% exhibited significant linear decline in average luminescence but only 18% showed a significant decline in luminescence range. Fifty-three per cent also showed a significant decrease in density.

Second, for the 10-year average series and all cores set to start in year 1, regardless of calendar year, calcification and luminescence range showed no clear pattern over the first 100 years of record (Fig. 4c, e). Skeletal density for the first 100 years of record was higher than the recent, 1891–1980, base period average and declined through time (Fig. 4a). Linear extension showed a less marked effect with no clear trend but was lower than the recent period average. Average luminescence (and maximum and minimum luminescence, not shown) was higher in the first 100 years of record compared to the recent average period and declined through time.

Finally, the three annual indices of coral luminescence for the long core from nearshore Havannah Reef (HAV01A) were compared over the period 1639–1985 (Fig. 5). Measured luminescence in this coral core was earlier noted to show a decline through time which was carried through to the final Burdekin River flow reconstruction and indicated a reduction in river flow through time (Isdale et al. 1998). The three series were significantly correlated (5% level) with the visual index and luminescence range $r = 0.79$, the average luminescence and luminescence range $r = 0.45$, and the average luminescence and visual index $r = 0.33$. All series were significantly correlated with the instrumental record of Burdekin River flow (1922–1985) with the highest correlation with the luminescence range ($r = 0.83$), followed by the visual index ($r = 0.78$) and lowest for the average luminescence ($r = 0.43$). Although there were similar inter-annual and decadal variations in the average luminescence and luminescence range series, only the average luminescence series showed a significant linear decrease through time.

Discussion

Measured coral luminescence variables from throughout the GBR were similar to those obtained by simple visual assessment of the intensity of luminescent lines. The visual luminescence indices used in earlier studies (e.g., HENDY et al. 2003; LOUGH et al. 2002; LOUGH 2007) were most comparable to annual luminescence range (from preceding winter minimum to current summer maximum) and annual luminescence maximum. This finding is of significance in that it means that the findings from these earlier, potentially

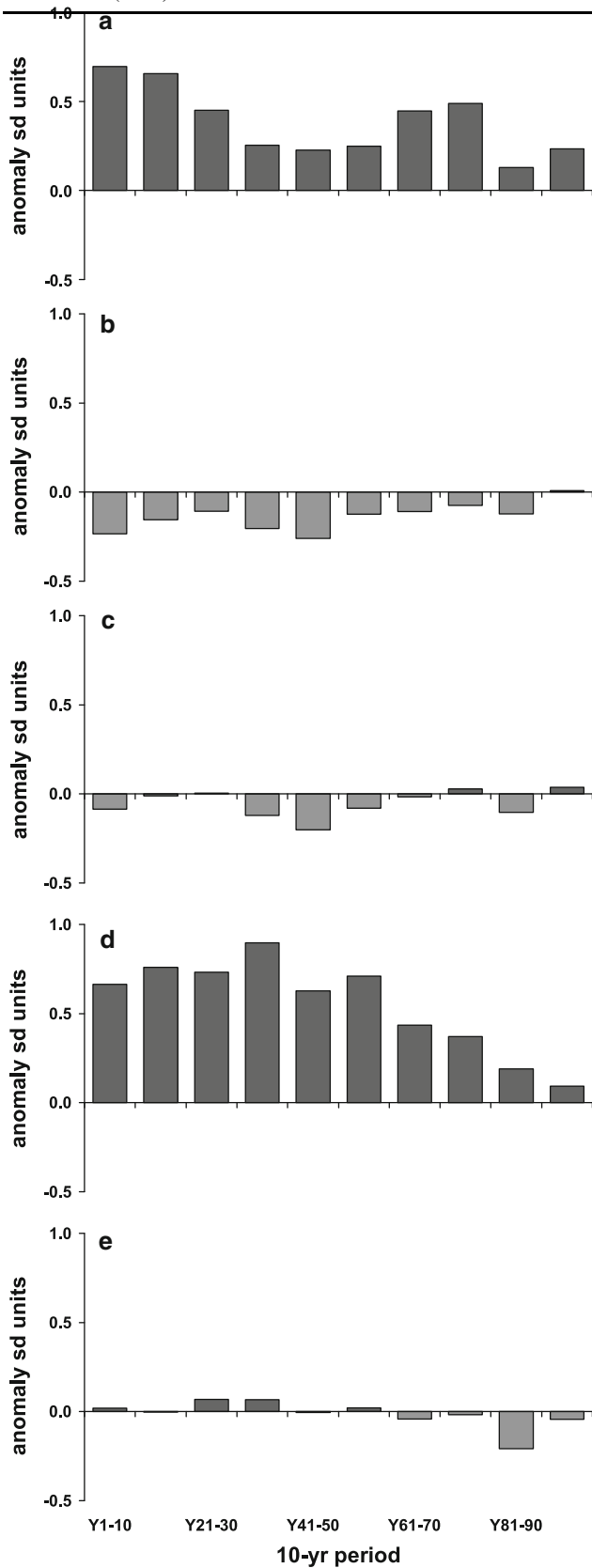


Fig. 4 Average standardized anomalies for 10-year periods; 43 cores (growth) and 37 cores (luminescence) for **a** skeletal density, **b** linear extension, **c** calcification, **d** average luminescence and **e** luminescence range

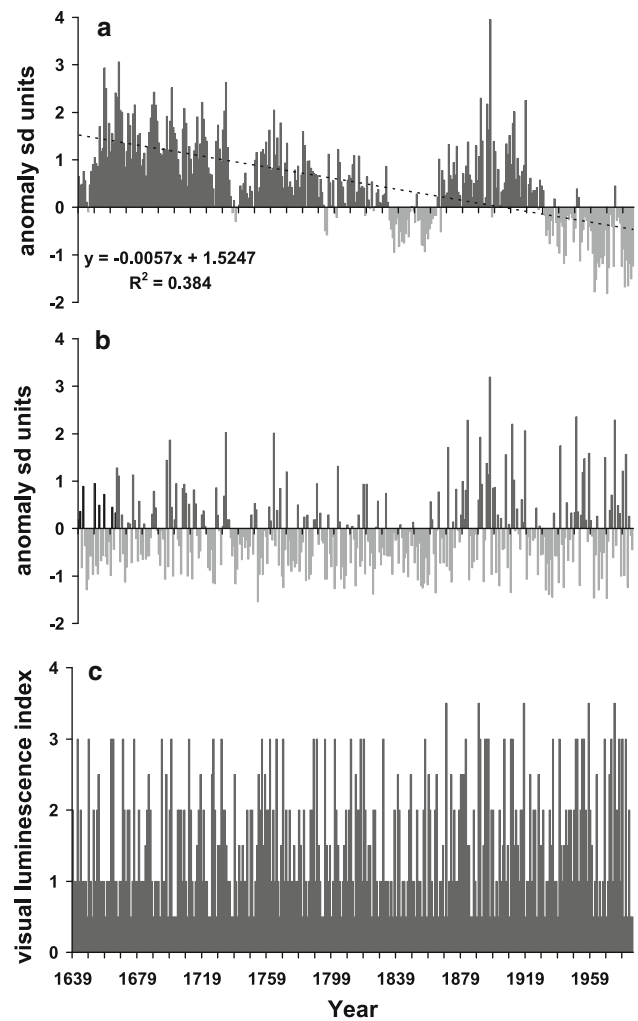


Fig. 5 Annual measured luminescence (as standardized anomalies from 1891–1980 mean and SD) for Havannah (HAV01A) long core, 1639–1985 for **a** average annual luminescence, **b** annual luminescence range, and **c** visual luminescence assessment index. Significant (at 5% level) linear regressions are also shown

subjective, assessments of luminescent line occurrence and intensity are still valid. It also suggests, that in the absence of luminescence measuring systems, at least for corals in nearshore environments with a hydrological regime similar to the GBR, that visual assessments of luminescent occurrence and intensity are useful—with the proviso that analyses (as in these earlier GBR studies are based on several coral samples, i.e., replication; Lough 2004). Measured luminescence ranges do, however, provide greater nuances of variability particularly for high luminescence values and do not fall to zero, as found for the visual index. The causes of measurable luminescence, and possible relationship with skeletal density, in corals from reefs unaffected by terrestrial freshwater (e.g., Barnes and Taylor 2001) are still unclear and worthy of further investigation.

Comparable linear extension rates were obtained when calculated from either adjacent density minima or adjacent luminescence minima. Again, this finding is useful. Measurement of linear extension rates from gamma densitometry (and X-ray densitometry) are based on the average density through the thickness of the coral slice (typically ~7 mm for *Porites*). Identification and hence measurement of annual density bands and derived growth variables can often be confounded by convoluted skeletal architecture (Barnes and Lough 1990; Lough and Barnes 1992). Measurements of coral luminescence using fluorescence spectroscopic techniques are made along the surface of the coral slice and so are less likely (though not completely) to be influenced by three-dimensional skeletal architecture. In circumstances where skeletal density does not provide a reliable measure of growth rates, measurements of surface luminescence can, therefore, be reliably used to obtain linear extension rates. Also, for Indo-Pacific *Porites*, linear extension rates are the primary variable controlling calcification rates (Lough and Barnes 2000; Lough 2008), whereas density is the primary control on calcification rates in Caribbean *Montastraea* (Carricart-Ganivet 2004). For *Porites*, therefore, measurements of linear extension from coral luminescence can provide a good estimate of calcification rates.

Of greater significance for the application of measured coral luminescence in nearshore reefs for reconstructing past river flow and rainfall is the evidence for a significant decline through time in average luminescence that appears to relate to colony age and does not appear to have an environmental basis. This finding could compromise the interpretation of published palaeoclimate reconstructions from coral luminescence (e.g., Smith et al. 1989; Isdale et al. 1998; Nyberg et al. 2007). The reason for this decline (that does not affect the luminescence range as maximum and minimum luminescence appear to be affected in a similar manner) is not immediately obvious. If, for example, luminescence is primarily due to humic acids and these degraded with time, then we would expect an increase in average luminescence towards the present. Another possibility is that corals' exposure to freshwater and hence the magnitude of average luminescence changes as the coral grows up through the water column. Although this mechanism could potentially affect data from the long coral cores, the decline with time was also evident in the small coral colonies analysed here which all came from similar, shallow-water environments. Also, a study of luminescence characteristics in 24 *Porites* colonies with depth (from 5 to 15–20 m) on a central GBR midshelf reef (Carricart-Ganivet et al. 2007) found no significant differences in measured luminescence variables with depth. In addition, if growth up through the water column was the cause of the observed decline, again we would expect an increase in

average luminescence through time. The only growth variable which also shows a significant change (decline) with time is average skeletal density (data presented here and Lough 2008). If, for example, Barnes and Taylor (2001) were correct that luminescence intensity is associated with lower density skeleton, then again we would expect an increase in average luminescence as skeletal density declines. This was not found. The reasons for declining skeletal density and declining average measured luminescence with age are, therefore, still obscure. The decline in density with age would also contradict Grove et al.'s (2010) suggestion that it is due to recent changes in the marine environment affecting coral growth rates. Their spectral green/blue ratio of luminescence intensity does, however, exclude any potential growth effect, as does the measured luminescence range described here, which also appears to be a reliable measure of luminescence intensity and can be used as a robust proxy for freshwater flow and rainfall.

In conclusion, summarizing the results of this study in relation to the original questions addressed:

- Visual and measured luminescence can provide similar records of the occurrence and relative intensity of freshwater floods
- The annual luminescence range and annual maximum luminescence are most closely related to river flows
- Average coral growth and luminescence characteristics are largely unrelated after allowing for spatial gradients in each
- Average, annual maximum and annual minimum luminescence all tend to decline through time which may be related to a similar decline in average skeletal density. This potential growth artefact does not affect the annual luminescence range which is considered to be the most robust luminescence proxy for assessing interannual and longer-term variations in tropical river flow and rainfall.

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