Seawater temperature trends, Great Barrier Reef, Queensland

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Abstract

Increasing seawater temperature along the Great Barrier Reef (GBR) is claimed to irreparably damage coral ecosystems, potentially leading to their demise. This research compares two sea surface temperature (SST) datasets measured in spring and early summer 1871 by NSW Government Astronomer Henry Chamberlain Russell with data collected over recent decades by the Australian Institute of Marine Science (AIMS). The 1871 data were collected during an expedition from Sydney to Cape York to observe the total eclipse of the sun. Similar quality data would not become available for well over seventy years, so this data provides a unique opportunity to determine if significant warming has occurred. No material difference was found between water temperature observed by Russell in 1871 and AIMS data. Within their bounds of uncertainty, the two datasets overlap. An analysis of a Bureau of Meteorology SST dataset at the AIMS wharf in Chunda Bay also shows no trend or change over the past 30 years. An interesting feature of the AIMS data, also reflected in the 1871 data, is that the water temperature in the most northerly parts of the GBR reaches a maximum of around 29-30°C early in the summer, and despite strong solar insolation, does not increase as the summer progresses. Temperature may even reduce in mid-summer due to high cloud cover from monsoonal influences. This may indicate that there is a maximum temperature that tropical waters can reach due to feedback mechanisms from tropical convection, clouds and evaporation.

Introduction

Scientific institutions, and government agencies have loudly and consistently claimed that the Great Barrier Reef (GBR) is imperilled by rising seas and increasing temperature and that carbon dioxide is ultimately to blame (Hoegh-Guldberg et al., 2007; Intergovernmental Panel on Climate Change, 2007; Maynard et al, 2011).

With concerns echoed by activists, the United Nations Educational, Scientific and Cultural Organisation (UNESCO), government, CSIRO, university alliances and main-stream media that the Reef may become seriously degraded or extinct due to climate change (Hughes et al., 2018; Australian Academy of Science, 2021; Great Barrier Reef Marine Park Authority 2024) it is timely to examine if sea surface temperature (SST) has increased, at what rate, and to what extent.

This research compares two high-quality sea surface temperature (SST) datasets measured in late spring and early summer 1871 by NSW Government Astronomer Henry Chamberlain Russell (Russell, 1877) with data collected over recent decades by the Australian Institute of Marine Science (AIMS). With allied scientists and assistants, Russell and colleague Robert Ellery from Melbourne Observatory, journeyed north from Sydney on the Queensland government-owned sail-assisted steamer, *S.S. Governor Blackall* to a vantage point off Cape Sidmouth near the tip of Cape York to observe the total eclipse of the sun, which was to occur on 12 December (Lomb, 2016). Initiated by the Royal Society of Victoria, the Australian Eclipse Expedition was the first major collaborative study jointly financed by the fledgling Australian colonies of Victoria, New South Wales and Queensland.

Seawater temperature was measured on both the northward and southward voyages between Port Stephens, NSW, and Morris Island east of Cape Sidmouth (Figure 1). To our knowledge, the dataset has not been compared with contemporary data before.

The study also examines average monthly maximum sea surface temperature (SST_{max}) reported by the Bureau of Meteorology (BoM) tide gauge on the AIMS wharf about 70 m from the northern shore of Chunda Bay, 25 km east of Townsville. Should SST_{max} have warmed rapidly over recent decades a trend should be observable in the almost 30-years of data.

Methods

1871 expedition data

Commencing off Port Stephens, NSW, from 28 November to 06 December, and on their return from 13 to 24 December, seawater temperature was measured using bucket samples drawn from near the bow of the steamer each hour between 6 AM and 6 PM while the vessel was in motion. Data provided in Table XXVI in Russell (1877) was transcribed, converted to Celsius, and abstracted as single or multiple values or averaged in blocks corresponding to tabulated descriptions such as *Off Cape Byron*. Averaging within days and between landmarks smoothed possible irregularities caused by discharges from major rivers, and in the vicinity of Moreton Bay, Brisbane.

Uncertainty of Russell's observations was assumed to be ±0.5°F which is ½ the interval range of a Fahrenheit mercury thermometer (equivalent on the Celsius scale to ±0.3°C). If several observations were averaged, sigma (σ) = $\sqrt{(\Delta x^2+\Delta y^2+..)}$ where Δ = 0.3°C, or if N>3, σ is the sample standard deviation (SD). For consistency, uncertainty was expressed as ±2σ, the band within which 95.4% of values are likely to occur. Russell's thermometer was expected to be similar in quality to others used for meteorological observations at Sydney Observatory, which were calibrated using Kew standards (Russell 1877 p. 4). Location coordinates were estimated using Google Earth Pro. The digitized 1871 dataset and calculations are available in the data supplement.

Australian Institute of Marine Science data

Loggers and automatic weather stations deployed by AIMS since the 1990s were searched at https://apps.aims.gov.au/ts-explorer/ to identify well-dispersed sites with reasonably complete and sufficiently long (>5-years) records. Daily maxima, minima and averages, standard deviations, data counts (N/day), and day-of-year (1 to 366) anomalies were calculated from high frequency (5-, 10- or 30-minute) quality-controlled raw data and identified by calendar and decimal dates using the statistical framework R (R Core Team, 2024).

AIMS temperature datasets spanned about 20 degrees of Latitude (about 3,000 km) between Bramble Cay and Anemone Bay, North Solitary Island, 28 km northeast of Woolgoolga NSW (Figure 1). While most sensors were deployed at variably shallow depths (0-5 m), one was deployed at 24 m (Tideman Cay), another at 7.4 m (19-138 Reef), and 10.6 m at North Solitary Island Anemone Bay.

As data for individual sites comprised varying numbers of observations/day, collected over variable time periods using a variety of dataloggers and sensors that were occasionally replaced at different aspects and depths, mean maxima, minima, averages, SDs and data counts (N/day) were derived for 21 timepoints through the year: 01 and 15 January (days 01, 15), 01 and 14 February (32, 45), 01 and 15 March (60, 74), 15 April (105), May (135), 15 and 30 June (166, 181), 15 July and August (196, 227), 01 and 15 September (244, 258), 01 and 15 October (274, 288), 01, 15 and 30 November (306, 319, 334), and 06 and 18 December (340, 352).

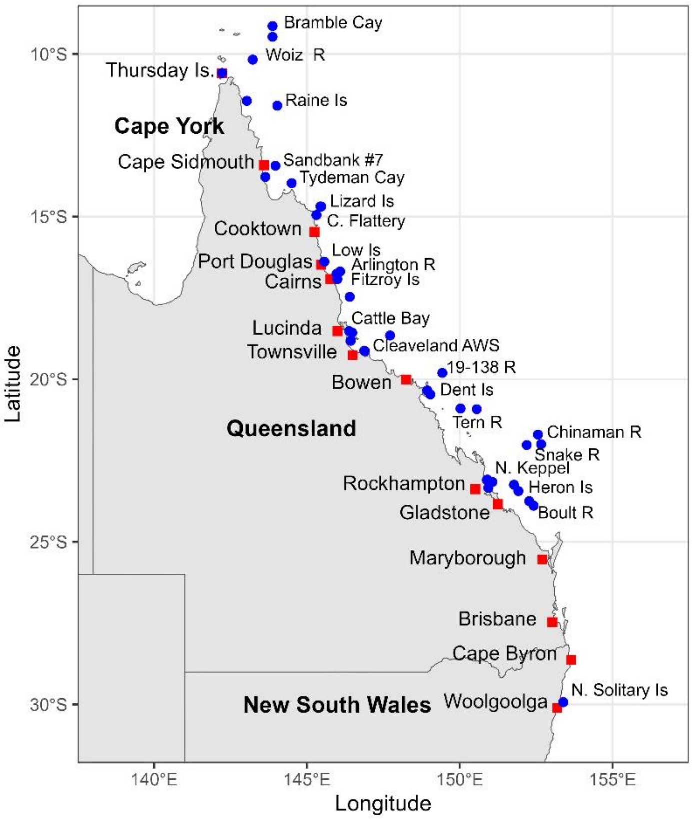

Figure 1. The 72 AIMS datasets (blue buttons) with some named for reference.

While a total of 221 AIMS datasets were examined many were clustered between Townsville and Cairns and in the vicinity of Gladstone, and many were too short or fragmented to be useful. The two reef flat and reef slope sites at Bramble Cay (FL1 and SL1) yielded only four observations/day, but were included as they marked the northern extremity of the Reef.

The AIMS data-matrix consisted of 21 columns corresponding to dates/days-of-the-year, and 72 rows of temperature data and associated statistics sorted by Latitude from Bramble Cay (-9.1395°) to a second North Solitary Island site at Elbow Cave (-29.9317°).

Cape Ferguson temperature data

The longest continuous SST dataset has been collected by the Cape Ferguson tide gauge located east of Townsville on the AIMS jetty (BoM site ID 59260). Mean monthly maxima (SST_{max}, °C) were downloaded from: Australian Baseline Sea Level Monitoring Project Monthly Sea Level and Meteorological Statistics (bom.gov.au). Reliable data commenced in October 1991 and with a few short breaks continued until April 2021 when temperature sensors apparently failed and were not repaired.

Data were compared with a range of climate variables obtained for the nearest grid-cell to the gauge (Latitude -19.25, Longitude 147.05) from: https://www.longpaddock.qld.gov.au/silo/. SILO data were summarised by months and years and aligned with BoM monthly solar exposure and Southern Oscillation Index (SOI) data. As variables with the exception of SOI exhibited conspicuous cycles, they were de-seasoned before analysis.

Statistical analysis

Comparison of the 1871 Expedition and AIMS data. Exploratory analysis undertaken using PAST from the University of Oslo (Hammer et al., 2001) found that while daily AIMS data were bimodal in their distribution overall, day-of-year data were normally distributed about their mean.

Multiple linear regression was undertaken using *Rcmdr* (Fox, 2005) and ancillary R packages, with independent variables: Latitude, Longitude and sensor depth (assumed to be constant for 1871 data). Quadratic terms for Latitude and Longitude were included to test for and account for non-linearity. Residuals were examined graphically. Scatterplots identified ill-fitting data and systematic drift relative to a 1:1 line (Piñeiro et al., 2008).

Regressions for 1871 and AIMS data were compared using 95% confidence intervals (CI_{95}) determined for a subset of 21 of the 72 AIMS datasets chosen to represent the Latitude range between Cape Sidmouth and the southern limit of the two *North* and *South* transects, a distance of about 2,600 km. Although depending on the record length and years sampled absolute SST-ranges/day were wider for AIMS data, 2σ estimated the CI_{95} interval for day-of-year means. The question is not whether the *mean*

SST by Latitude responses in 1871 were different to contemporary AIMS data (indicating that 1871 may have been a cooler or warmer year), but considering year-to-year variation, which is natural, whether differences could be regarded as meaningful.

Cape Ferguson SST_{max} was also analysed using multiple linear regression of the form: $SST_{max} \sim t + x_1 + x_2 .. x_n$, where, *time* (t) is expressed as month-centred DeciYears (Year + (month-0.5)/12), and ($x_1..x_n$) are de-seasoned climate covariates for the SILO grid-cell and solar exposure, and the 3-point running mean of the monthly SOI (SOI_{3pt}).

Results

The 1871 expedition data.

On the journey north to Cape Sidmouth from 28 November to 06 December, seawater temperature increased approximately 4°C along the body of the Reef (Figure 2(a)). Temperatures observed on the return journey from 13 to 24 December had warmed significantly over the intervening period ($F_{3,24}$, 6.4, p = 0.002). The later transect showed that with the approaching summer Solstice and the sun seemingly directly overhead, the rate of warming lessened considerably north from Townsville (i.e., as SST increased, curvature increased also (Appendix, Table 1)).

While Longitude (distance from the coast) was not statistically significant overall (ns, p >0.05), $Latitude_{poly(2)}$ explained >90% of variation in SST (R^2_{adj} = 0.937 (Northern transect) and 0.930 (Southern transect)). As fitted values were distributed linearly and randomly about the 1:1 line in Figure 2(b), analysis is unlikely to be biased by unknown factors.

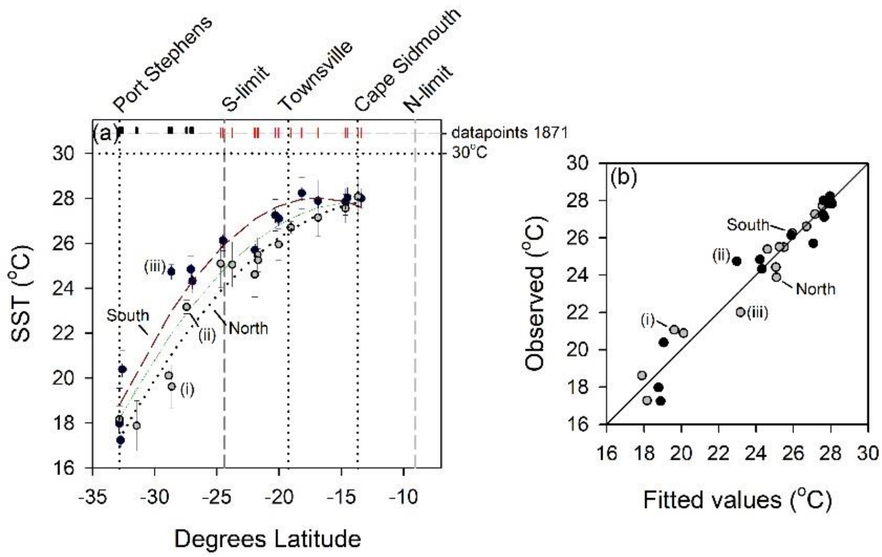

Figure 2(a). Seawater temperatures north from Port Stephens from 28 November to 6 December 1871 and on return south from Cape Sidmouth from 13 to 24 December (grey and black circles). The dashed centreline shows the average trajectory while vertical bars indicate 95% (±2σ) instrument and sampling uncertainty. Datapoints (i) and (iii) are *Cape Byron*, and (ii), *Point Lookout, N. Stradbroke Island*. Goodness of fit (observed vs. fitted values) relative to the 1:1 line is shown in (b).

Comparisons of 1871 data with recent AIMS data

Figure 3 compares expedition data for the 28 November to 06 December north from Port Stephens to Cape Sidmouth in 1871, with the 21-site subset of AIMS data for 06 December; and for the return journey south from 13 to 24 December, with 18 December AIMS data. 06 December and 18 December approximate each journey's mid-point.

The coloured areas show 95% prediction intervals for respective 1871 quadratic ($poly_{(2)}$) fits calculated by the R package *ggplot2* (Wickham, 2016). These indicate the range in which predictions would lie if the journeys were repeated. It is emphasised that while error-bars for expedition data comprise both instrument and sampling uncertainties, those for AIMS data are calculated as 2σ where σ is the SD of day-of-year values from which means were calculated

As curves for the expedition, and the 21-site AIMS subset confidence intervals, overlap, and particularly given the 2σ range within which 95.4% of AIMS data for respective days lie (and that absolute extremes are outside that range), while the year may have been cooler, it could not be claimed that water temperature in 1871 was materially different to temperatures measured by AIMS over recent decades.

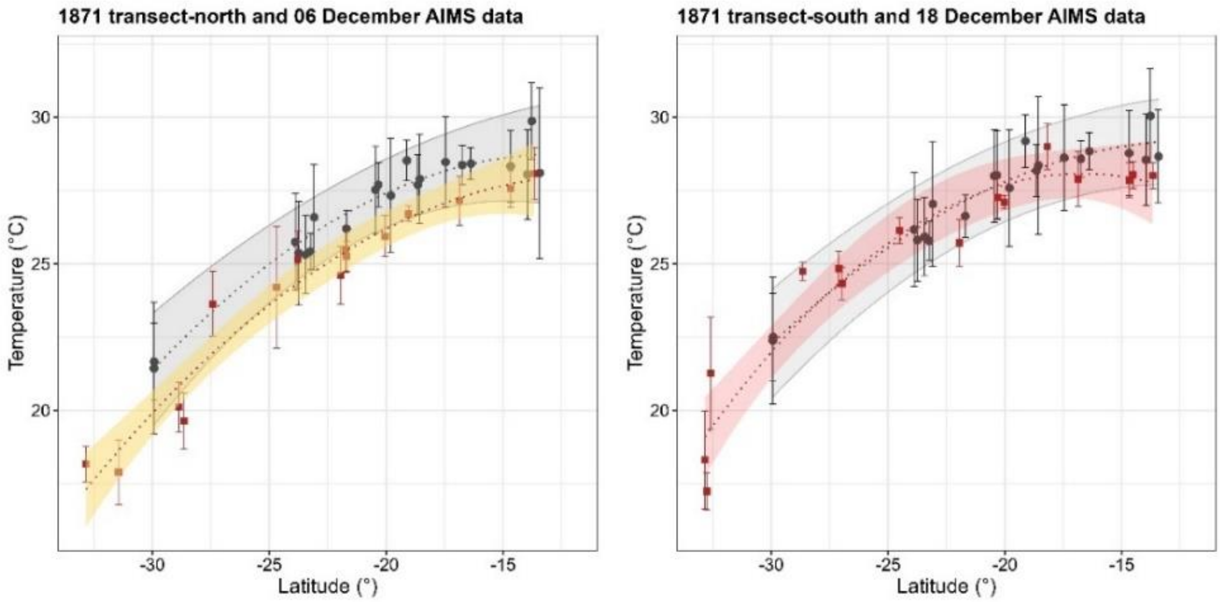

Figure 3. Comparison of 1871 expedition data and AIMS data. 1871 Expedition data (28 November to 6 December (left), and 13 to 24 December (right) – brown squares, error bars indicate ±2σ uncertainty as explained in Methods. Coloured bands show 95% prediction intervals for respective poly$_{(2)}$ fits (dashed lines). Black circles show day-of-year means ±2σ error bars for the 21 selected AIMS datasets for the 06 and 18 December. The filled grey areas show upper and lower uncertainty bands calculated as upper = poly$_{(2)}$(mean + 2σ) and lower = poly$_{(2)}$(mean - 2σ).

1871 Expedition data in the context of within- and between-year variation

The 1871 Expeditioners traversed the Whitsunday Passage (Heron Island) on 02 December (travelling northward) and the 17 December (travelling southward), Magnetic Island (Cleveland Bay) on 03 and 16 December, Lizard Island on 05 and 14 December, and Fitzroy Island on 04 and 15 December. For those reefs, Figure 4 shows the 1871 data overlain onto the annual cycle derived from AIMS data, and to indicate spread, data for the years from which means and SDs were derived. Figure 4 shows average SST reaches a maximum in late December that changes little until the summer Equinox on 21 March.

Considered in context, differences between the 1871 and recent AIMS data are less than the annual cycle, typically about 6°C, and also 1871 data are within the ±2σ bandwidth of inter-year variation in AIMS data for those reefs.

Temperature change in late summer

It is evident from Figure 4 that there is little change in temperature after the end of December. To explore this further, Table 2 shows the SST at various locations in the northern GBR. While reef flat temperatures at Woiz Reef, Thursday Island, Wallace Island, Raine Island and Wilkie Island change little between late December and mid-March, SST declines somewhat with distance north.

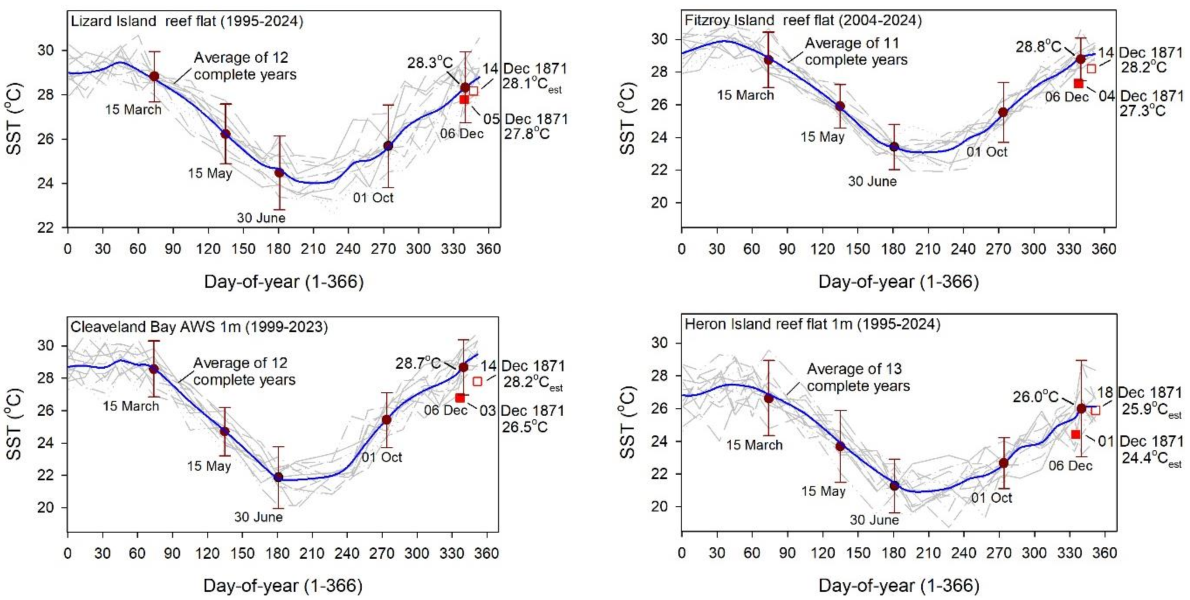

Figure 4. Temperature profiles for Lizard and Fitzroy Islands, Cleaveland Bay AWS and Heron Island (locations shown in Figure 1) showing average SST, the spread of years from which means were calculated (grey lines), 2σ error-bars for nominated days, and actual (or estimated) values for dates when the expedition passed in 1871 (solid and hollow red squares).

Table 2. Maximum, minimum and average SST at various locations in late summer. Despite the sun moving north from the Tropic of Capricorn after 8 December, for the northern-most datasets, maximum, minimum and mean SST changed little from 01 January to the autumn Equinox on 22 March. While the mean across sites on 14 February is 29.2°C, average SST_{max} is only 29.8°C. (FL refers to reef flats and N is the number of years over which averages were calculated.)

Site	Logger ID		SST_{max}	SST_{min}	SST_{mean}
Woiz Reef	WOIZFL1	1-Jan	30.4	29.3	29.9
Lat -10.17	N = 7	14-Feb	30.0	29.0	29.5
		15-Mar	29.5	29.0	29.4
		Mean	30.0	29.1	**29.6**
Thursday Is.	TURFL1	1-Jan	30.0	29.2	29.7
Lat -10.58	N=11	14-Feb	29.9	29.3	29.6
		15-Mar	29.7	29.0	29.3
		Mean	29.9	29.2	**29.5**
Wallace Is.	WALFL1	1-Jan	30.5	28.8	29.6
Lat -11.44	N=9	14-Feb	30.4	29.5	30.0
		15-Mar	30.1	28.9	29.7
		Mean	30.3	29.1	**29.8**
Raine Is	RAIFL1	1-Jan	29.5	28.0	28.6
Lat -11.59	N=8	14-Feb	29.6	28.3	29.0
		15-Mar	29.1	28.1	28.5
		Mean	29.4	28.1	**28.7**
Wilkie Is.	WILKFL1	1-Jan	30.4	29.8	30.1
Lat -13.78	N=7	14-Feb	30.7	29.8	30.2
		15-Mar	30.0	29.2	29.6
		Mean	30.4	29.6	**30.0**

Critical to understanding evolution of the warming cycle (Figure 5), is that as the sun moves toward the Equator from is zenith at the Tropic of Capricorn (Latitude -23.43°) on 21-22 December, although SST warms southwards, the rate of increase (curvature) declines markedly north of Townsville, to become static or trend negative north of Latitude -13.5°, which coincidently is the Latitude of Cape Sidmouth.

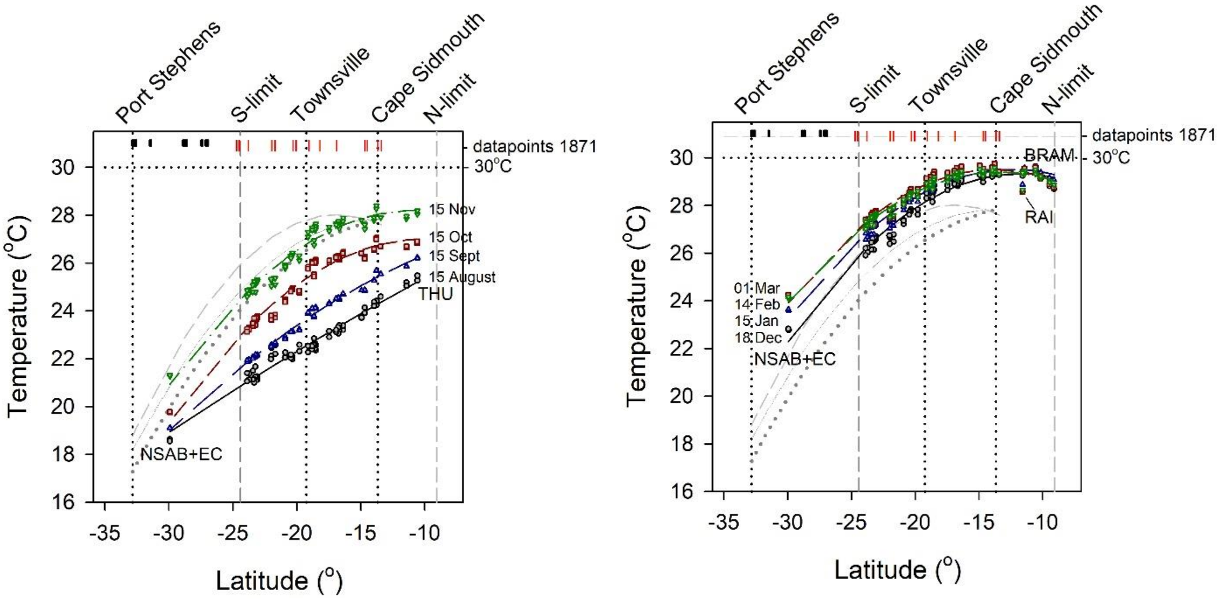

Figure 5. The warming cycle from 18 August to 15 November (left) and through summer from 18 December to 01 March (right), shown with covariate-adjusted values for 71 reef flat and reef slope sites, overlaid on 1871 data trajectories. NSAB refers to North Solitary Island, Anemone Bay, BRAM, Bramble Cay.

Although a Latitudinal limit to warming (the apparent vertex in Figure 5 and Appendix 1), with possible cooling towards the Equator has not been identified previously using in-situ data, the average SST_{max} limit for the northern-most sites in mid-February (29.7°C, Table 2) is within the range of studies that reference thermoregulation of tropical oceans between 27°C to <30°C (e.g., Wallace, 1992; Waliser and Graham, 1993; Clement, et al., 1996; Sud et al., 1999).

Cape Ferguson SST_{Max} data

Figure 5(a) shows the 30-year long SST_{Max} temperature dataset for Cape Ferguson, Figure 5(b) shows the same data with the seasonal cycle removed overlaid by the SOI_{3pt}.

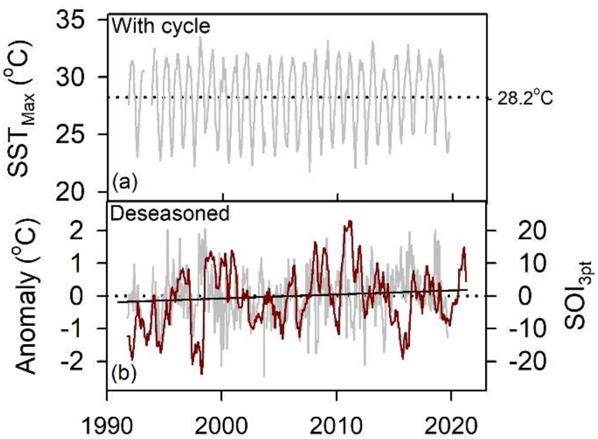

Figure 5. Cape Ferguson SST_{Max} (a), and in (b) with seasonal cycle removed (October 1991 to April 2021). The apparently significant trend of 0.137°C/decade ($F_{3,319}$, 6.07, p = 0.014) indicated by the least squares line in (b), which explained only 1.6% of variation in SST_{Max} (R^2_{adj} 0.016) was spuriously due to variation in climatic covariables associated with the El Niño Southern Oscillation (RED solid line, right axis), which itself exerted no significant effect on SST_{max} (p>0.05).

The latter part of the period experienced prolonged negative phases of the SOI, which is associated with warmer GRR water temperature, and this is largely responsible for the small apparent increase in temperature.

Prolonged negative phases of the SOI (1997-1998, 2005, 2010, 2014-2016, 2018-2020) are associated with clear skies, lower rainfall and increased temperature, while increased mean sea-level pressure results in reduced sea-levels at extreme low tides and increased exposure of shallow reefs and reef slopes. Accounting for climatic covariables using multiple linear regression resulted in no residual trend that could be attributed to warming of the East Australian Current adjacent to Cape Ferguson. As conditions associated with ENSO are natural, they should not be confused with long-term warming.

Discussion

1871 expedition and AIMS data

While 1871 temperatures near Port Stephens and Cape Sidmouth were similar at the commencement and end of both journeys (18.2°C and 18.7°C, and 28.7°C and 28.2°C travelling north and returning south respectively), SST was significantly warmer on the return journey than for the forward journey, particularly in the vicinity of Townsville where it was higher by about 1.8°C. AIMS response curves were within the 95% confidence bands for the north-bound transect from 01 to 15 November, thus, considering data imperfections, slight differences in timing, weather effects etc. over which there is no control, no material difference could be claimed between respective datasets at those times. For the southbound journey in December, transects were also within 95% confidence bands of AIMS data from 18 December to 15 January.

Cape Ferguson SST_{max} and SST moderation along the Reef Lagoon

After accounting for de-seasoned Tmax, rainfall and barometric pressure for the adjacent SILO grid-cell (which together explained 18% of variation in de-seasoned SST_{max}), no trend or change was detectable in SST_{max} at Cape Ferguson from October 1991 to April 2021 (29.5 years) that could be attributed unequivocally to global warming or climate change.

An Ocean Thermostat

An interesting feature of the temperature data is that the maximum temperature of 28 to 29°C is reached relatively early in the summer (December) in the north, but not until February further south at about Latitude -20° (Figure 5). The annual temperature variation at the most northly part of the GBR (Latitude -10°) is around 3°C (25.5°C to 29°C), but is around 6°C at its southern-most limit of Latitude -24°. In addition, SST_{Max} in the latter part of summer, occurs south of the Reef's northern limit at Barmble Cay, resulting in a temperature peak of around 29.5°C at Latitude -13.5°.

Why is the temperature at the most northern part of the GBR in late summer slightly less than areas further south? The reason is possibly due to the effect of clouds on the radiation balance. The build up to the early part of the north Australian monsoon in late November and December is characterised by relatively clear skies which produces very high insolation rates and strong surface heating. By January, the wet season has usually started and there are more clouds restricting insolation. It is likely that the most northerly parts of the GBR are cloudier than the area further south, reducing the effective heating of the surface by the sun. Thus, the most northerly parts of the GBR become slightly cooler than south of Latitude -13.5°

Another notable feature of the data is that the average maximum temperature along the length of the Reef is about 29.5°C which is similar to the seawater temperature in the Indo-pacific warm pool (Peixoto and Oort, 1992). This is the region of water between PNG, Indonesia and Thailand and is the hottest major water mass in the world. Why does the water temperature not exceed this threshold?

The reason is that evaporative heat losses from the sea surface increases dramatically with a small increase in water temperature - by 7% per degree Celsius (as described by the Clausius Clapeyron relation). This is a very powerful feedback mechanism restricting any seawater temperature rise due to an increased radiative forcing. The latent heat energy added to the atmosphere by evaporation is ultimately radiated to space near the top of the atmosphere, after energy is transported vertically in deep convection cells (thunderstorms), which are driven by latent heat energy. Thus, the increased evaporative cooling of the ocean surface, not only cools the ocean, it also has the effect of cooling the planet.

The latent heat energy loss by the water surface in tropical waters is typically around 100 W/m2 (corresponding to an evaporation rate of 4 mm/day) so an increase in water temperature of 1°C would increase the evaporative heat losses to around 107 W/m^2. To put this in context, the global average net radiation imbalance caused by all anthropogenic sources estimated from 1750 to 2019, is calculated from the IPCC AR6 report to be between 2 and 3.5 W/m^2. It is thus evident that the exponential increase in evaporation is a very powerful negative feedback mechanism limiting maximum temperatures. In addition, a water temperature change of less than 1°C causes an evaporative cooling that is larger than the radiative balances caused by increasing CO^2 concentrations.

Conclusion

Sea surface temperature observed by scientists in 1871 is within the bounds of year-to-year variation measured by AIMS dataloggers and weather stations along the length of the Reef. It could therefore not be claimed that SST in 1871 is materially different to contemporary AIMS data. Further, the lack of trend in Cape Ferguson SST_{max} does not support the proposition that SST has materially warmed due to anthropogenic factors over the past 30-years.

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Appendix 1.

Regression coefficients and vertex coordinates (*h*, *k*) for each of the 21 timepoints analysed. Note that *h* was not within the data domain (shaded) between March and November.

		Regression coefficients $SST = ax^2 + bx + c$				Vertex coordinates	
						$h = -b/2a$	$k = f(h)$
Date	Day	*a*	*b*	*c*	R^2	(° Latitude)	(°C)
01 Jan	1	-0.020	-0.474	26.69	0.963	-11.78	29.49
15 Jan	15	-0.020	-0.501	26.42	0.972	-12.37	29.52
01 Feb	32	-0.023	-0.635	25.15	0.953	-13.87	29.55
14 Feb	45	-0.021	-0.589	25.46	0.956	-13.76	29.51
01 Mar	60	-0.020	-0.536	25.82	0.975	-13.41	29.41
15 Mar	74	-0.014	-0.311	27.34	0.975	-11.43	29.12
15 Apr	105	-0.005	0.027	29.48	0.995	*2.46*	29.51
15 May	135	0.001	na	30.54	0.973	na	na
15 Aug	166	0.005	na	30.95	0.926	na	na
30 Jun	181	0.006	na	31.13	0.918	na	na
15 Jul	196	0.004	na	30.46	0.945	na	na
15 Aug	227	0.000	na	29.00	0.977	na	na
01 Sept	244	-0.006	na	27.73	0.997	na	na
15 Sept	258	-0.009	-0.001	26.99	0.993	*-0.04*	26.99
01 Oct	274	-0.015	-0.226	25.58	0.974	*-7.77*	26.46
15 Oct	288	-0.020	-0.421	24.67	0.971	*-10.52*	26.88
01 Nov	306	-0.026	-0.661	23.29	0.947	-12.66	27.47
15 Nov	319	-0.022	-0.526	24.83	0.955	-11.94	27.97
30 Nov	334	-0.023	-0.535	25.54	0.969	-11.82	28.71
06 Dec	340	-0.023	-0.549	25.76	0.968	-11.92	29.04
18 Dec	352	-0.021	-0.504	26.36	0.962	-11.79	29.34

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