Sea level and sea-surface temperature at Townsville, Great Barrier Reef, Queensland – a case study

Part 2. Trends in sea surface temperature

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Abstract

Analysis of sea surface temperature (SST) from October 1991 measured at the Cape Ferguson tide gauge in a bay adjacent to the central Great Barrier Reef, 24 km east of Townsville, Queensland, found terrestrial maximum temperature (Tmax) explained most variation ***IN*** SST, followed by (-) barometric pressure (hPa). However, as R^2_{adj} = 0.407 a considerable proportion of variation in SST was unexplained. Including a non-trending underlying signal that impacted ***ON*** SST resembling the Pacific Decadal Oscillation, increased variation explained to 0.470. Unexplained variation was reasoned to be due to the passing East Australian Current, for which there was no parallel data.

SST measured close to shore is impacted on by heat exchanges with the landscape especially during periods of low summer rainfall when Tmax is axiomatically higher. Although hysteresis was evident in cooling *vs*. warming cycles no trend or change in SST at Cape Ferguson could be attributed to the climate or factors such as CO_2.

In November 1871 astronomers from Melbourne and Sydney sailed to Cape Sidmouth near the top of Cape York to observe the total eclipse of the sun. Their observations of SST from Port Stephens and return were used to baseline recent data derived from 27 Australian Institute of Marine Science (AIMS) dataloggers from Thursday Island in the north, to North Solitary Island in the south. Both datasets were robust, comparable and fit for the purpose of examining time-evolution of SST. AIMS data for equivalent times and latitudes were not significantly different to data measured in November/December 1871.

Maximum SST was predicted to be 29.64°C in late-January to early-February at Latitude -13.5°, which by coincidence is about the Latitude of Cape Sidmouth. By mid-August SST declined to 24.26°C before increasing to 27.96°C by mid-November after which the cycle repeats. The interannual range at Latitude -13.5° was therefore 5.4°C, while to the south at Heron Island (Latitude -23.43) it was 6.9°C (20.87°C in mid-July to 27.80°C in mid-February). The adaptive range of the Reef is closely regulated between 27°C to >29°C but <30°C for up to five months and >20°C during winter (July to September). The water cycle operates as a self-regulating heat-pump that maintains SST within close limits. There is no evidence that the process has broken-down or is likely to do so in the future.

It is concluded that there is no evidence that SST has increased in recent decades or the Great Barrier Reef is imperiled or endangered by global warming or climate change.

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1. Introduction and methods

Sea surface temperature (SST) has been measured at Cape Ferguson, south of Townsville, Queensland, since September 1991 (Latitude -19.2774°, Longitude 147.0586°) as a component of the Australian Baseline Sea Level Monitoring Project (ABSLMP), which aims to identify changes in oceans surrounding Australia that could be attributed to the enhanced greenhouse effect. It is expected that should anthropogenic warming affect ocean temperature, a trend would be evident in the 30-year monthly dataset. Located on the Australian Institute of Marine Science (AIMS) wharf about 70 m from the shoreline, the site is managed by the National Tide Centre, a unit within Australia's Bureau of Meteorology (BoM). Site-summary metadata is available from BoM's climate data online facility (Station ID 32182).

With operations in Townsville, Darwin and Perth, AIMS is part of arguably the largest, most expensive and elite conglomerate of research institutions in Australia. Spread across multiple universities and state and commonwealth agencies, and well supported by the Australian Research Council and direct grants their research focuses on the effect of climate change on Australia's Great Barrier Reef (GBR). They and partner organisations including CSIRO and the Great Barrier Reef Marine Park Authority (GBRMPA), Great Barrier Reef Foundation, WWF and the Climate Council have consistently claimed survival of the Reef is imperiled by rising sea levels and anthropogenic warming. For instance, GBRMPA states unequivocally[1] that "Australia's climate has warmed on average by 1.44 degrees Celsius since national records began in 1910, with most warming occurring since 1950 and every decade since then being warmer than the ones before"; and that "sea surface temperatures in the Australian region have warmed by around 1 degree Celsius since 1910, with the Great Barrier Reef warming by 0.8 degrees Celsius in the same period".

The purpose of this Research Report is to present an analysis of the mean monthly SST dataset for Cape Ferguson and selected AIMS data to test that claim. The main research question is:

- Is mean monthly SST increasing, and if so, at what rate.

The question is posed as a hypothesis of the form: SST ~ Time + x_1 + … + x_n;

where, x_1 + … + x_n; are possible independent concomitant variables and time is expressed as month-centred DeciYears (Year + (month$_{(1\text{ to }12)}$ - 0.5)/12). Analysis aims to distinguish between variables that cause variation ***IN*** SST data (covariables - x_1 + … + x_n), from latent factors that may have impacted ***ON*** the data-stream (impact variables) such as a bump to a monitoring site or a change in instruments.

1.1 Data sources and statistical methods

Independent variables (x_1 to x_n) were monthly rainfall (mm) and average maximum temperature (Tmax, °C) for the SILO grid-cell closest to the gauge (https://www.longpaddock.qld.gov.au/silo/; Latitude -19.30, Longitude 147.05); average daily solar exposure (MJ/m^2); the 3-point running mean of the monthly BoM Southern Oscillation Index (SOI_{3pt}); mean monthly sea level (MSL, m), which was analysed in Part A, and average monthly barometric pressure (hPa). Tide gauge data was downloaded from http://www.bom.gov.au/oceanography /projects/abslmp/data/monthly.shtml and SOI and solar exposure data were obtained from the BoM.

AIMS sea surface temperature datasets (https://apps.aims.gov.au/metadata/view/4a12a8c0-c573-11dc-b99b-00008a07204e) were searched to identify and acquire shallow-water temperature time series, to provide wider context to the study.

[1] https://www.gbrmpa.gov.au/our-work/threats-to-the-reef/climate-change/sea-temperature

Hypotheses were investigated using multiple linear regression (MLR) using R[1] and the *Rcmdr*[2] package, supported by sequential analysis of variance (aov). Residual homogeneity was evaluated using sequential t-test analysis of regime shifts (STARS), more recently updated as the SRSD method (Sequential Regime Shift Detection; see https://sites.google.com /view/regime-shift-test).

2. Cape Ferguson

As discussed previously in Part A, variables with the exception of SOI were dominated by seasonal cycles (Figure 1). Seasonality ($Month_{factor}$) explained 37.8% of variation in rainfall; 87.7%, in Tmax; 75.9% in solar exposure; 86.1% in barometric pressure; 93.0% in SST and 57.6% in MSL. Seasonal cycles have no trend, they impart considerable 'noise', they result in residual autocorrelation and because they may inflate variation explained (R^2_{adj}) data except for SOI_{3pt}, were made seasonally stationary by deducting monthly grand means from respective monthly values. Such transformed data are referred to as anomalies.

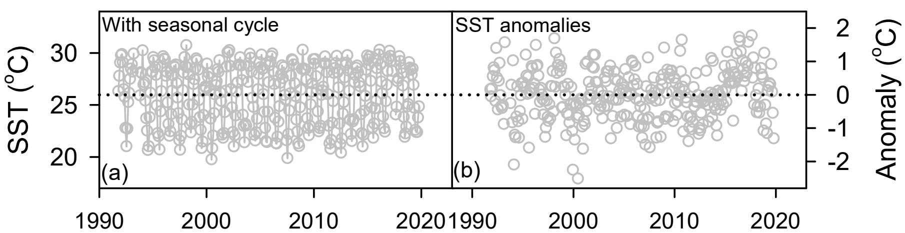

Figure 1. Sea surface temperature with its embedded seasonal cycle (a), and in (b), the same data with the seasonal signal removed.

2.1 Mean monthly sea surface temperature

Although data are time-ordered, they were not analysed as time-series. Exploratory analysis examined significance of variables as predictors of SST. Variables were then ranked in order of F-values and re-analysed sequentially. Sequential (Type 1) analysis of variance (aov) with all variables considered is shown in Table 1.

Table 1. Sequential aov of the effect on $SST_{anomaly}$, of independent predictors and lags (L_N) thereof, previously ranked by F-value. Contribution to the total sum of squares (which estimates the total variation in SST) has been proportioned to the nominated predictors. As unexplained (residual) variation >50% influential factors may be missing. (R^2_{adj} = 0.411; shaded Pr(>F) values were not significant.)

Source of variation	Sum of squares	Percent of total SS	Df	F-value	Pr(>F)
$Tmax_{anomaly}$	67.43	37.54	1	206.39	<0.001
$hPa_{anomaly}$	4.32	2.40	1	13.22	0.000
$Rain_{anomaly}$	2.38	1.32	1	7.27	0.007
SOI_{3Pt}	0.68	0.38	1	2.08	0.150
$MSL_{anomaly}$	0.07	0.04	1	0.21	0.645
$Rain_{anomalyL2}$	0.06	0.03	1	0.19	0.663
$SolarMJ_{anomalyL1}$	1.10	0.61	1	3.37	0.067
$Tmax_{anomalyL2}$	0.00	0.00	1	0.00	0.995
$Rain_{anomalyL1}$	0.02	0.01	1	0.05	0.811
Residual	103.56	57.66	317		
Total sum of squares	179.61				

[1] R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

[2] https://cran.r-project.org/web/packages/Rcmdr/index.html

Terrestrial $Tmax_{anomaly}$ explained most of the variation in $SST_{anomaly}$, with small contributions also from rainfall and hPa anomalies. While $SolarMJ_{anomalyL1}$ may have been influential (P = 0.06), others that were not significant (P >0.10) were discarded.

As they explained too little variation and were not significant, step wise second round analyses eliminated further variables in Table 1 including $SolarMJ_{L1}$ and $Rain_{L1}$ anomalies (Table 2).

Table 2. Sequential aov of the response of monthly SST anomalies to significant predictors. As the effect of rainfall on SST was negligible it was discarded. The MLR relationship explained 40.7% of variation in SST, slightly less for Table 1. Note that while proportions changed slightly, Total sum of squares, which estimates total variation in $SST_{anomaly}$, is the same as previously.

Source of variation	Sum of squares	Percent of total SS	Df	F value	Pr(>F)
$Tmax_{anomaly}$	67.426	37.54	1	206.45	<0.001
$hPa_{anomaly\ (neg)}$	6.162	3.43	1	18.87	<0.001
$Rain_{anomaly}$	0.535	0.30	1	1.64	0.216
Residuals	105.49	58.73	323		
Total sum of squares	179.61				

Removing non-significant variables slightly reduced the proportion of variation explained (R^2_{adj} 0.407 *vs*. 0.411 previously); however, explanatory variables that don't explain significant variation cannot be hypothesised as being influential because they 'should' or 'must' be. Thus, even though $SolarMJ_{L1}$ and $Rain_{L1}$ anomalies may affect Tmax; on their own they had no measurable effect on SST. Also, variables that influence MSL, including SOI_{3pt} (and MSL itself) showed no relationship with SST. However, as R^2_{adj} was less than 50% (0.50), the overall relationship was imprecise. (Due to the lack of parallel data, the effect of passing currents on SST measured by the tide gauge could not be estimated.)

Table 2 shows only two of the original nine variables directly influenced SST and that while the relationship with terrestrial Tmax was positive, the effect of barometric pressure (hPa) was negative (Figure 2).

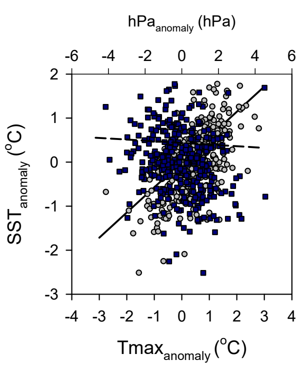

Figure 2. A 2-D scatterplot showing that while $SST_{anomaly}$ increases with $Tmax_{anomaly}$ (circles, dark solid line), it declined slightly as barometric pressure ($hPa_{anomaly}$) increased (blue squares). Thus, highest $SST_{anomaly}$ was associated with high Tmax and low hPa. Note that conditional on Tmax (Table 2), the $hPa_{anomaly}$ relationship was not significant on its own (P = 0.43).

Decomposition of the $SST_{anomaly}$ signal follows the methodology outlined in Section 3.1.1 of Part A. Variables and factors are additive; that is, the total SST signal comprises the seasonal cycle, already removed (Figure 1), effects due to covariables that cause variation ***IN*** SST data (Figure 3(a)), and those that may impact ***ON*** the data-stream (Figure 3(b)).

Final-round analysis verified that variables and step-changes combined were significant; that segmented regressions were not coincident (covariate-adjusted segment means were different) and that segmented relationships were parallel (interaction was not significant), which verifies that segmented responses to covariables was the same.

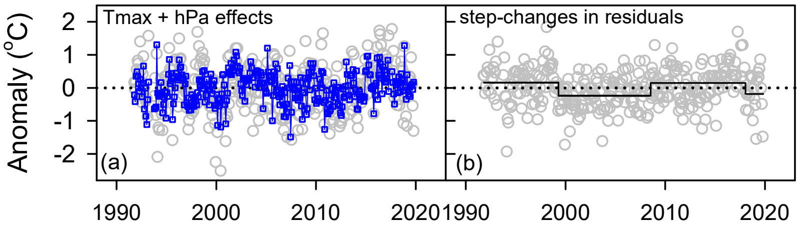

Figure 3. The combined effect of Tmax and hPa anomalies overlaid on deseasoned SST (a); and the residuals for that fit overlaid by step-changes which were detected independently.

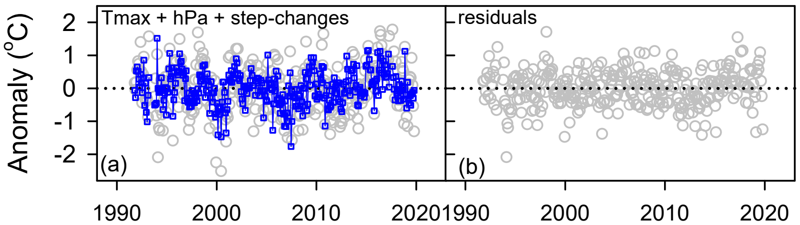

Figure 4. The combined effect of variables causing variation *IN* $SST_{anomaly}$ (Tmax and hPa anomalies) and those that cause impacts *ON* the data-stream (shifts or step-changes in the mean), overlaid on SST anomalies (a), and residuals resulting from the fit (b).

The analysis (Table 3) explained 47.0% of variation in $SST_{anomaly}$ (vs. 40.6% for $Tmax_{anomaly}$ + $hPa_{anomaly}$ together), thus, much of the variation was still unexplained.

Table 3. Analysis of variance of the final model that includes the categorical shift variable (Sh) defining step-changes shown in Figure 3(b). Inhomogeneities in May 1999, July 2008 and January 2018 explained 11.0% of additional variation that could not be explained previously (Partial R^2 = (Rss_{Table2} – Rss_{Table3})/ Rss_{Table3}).

Source of variation	Sum Sq	Percent of total SS	Df	F value	Pr(>F)
$Tmax_{anomaly}$	67.426	37.54	1	230.87	<0.001
$hPa_{anomaly\ (neg)}$	6.162	3.43	1	21.10	<0.002
$Sh_{SSTresidual}$	11.693	6.51	1	40.04	<0.003
Residual ss	94.332	52.52	323		
Total sum of squares	179.61				

Shifts in May 1999, July 2008 and January 2018 (Figure (3b)) could not be explained by site-summary or other metadata. Satellite images show the wharf supporting the tide gauge is solidly anchored, probably into bedrock and there is no evidence of impacts to the wharf, which appears to be a concrete deck suspended on piers. Furthermore, step-changes in the mean in Figure 3(b) oscillate around the zero-centre of the residual data. So, there was no SST trend, but there was a latent signal, which although not related to Tmax or barometric pressure may still be climate-related.

According to http://research.jisao.washington.edu/pdo/ the Pacific Decadal Oscillation (PDO) "*is a long-lived El Niño-like pattern of Pacific climate variability. While the two climate oscillations have similar spatial climate fingerprints, they have very different behavior in time … Two main characteristics distinguish PDO from El Niño/Southern Oscillation (ENSO): first, 20th century PDO "events" persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months ….*" Further …. "*Causes for the PDO are not currently known. Likewise, the potential predictability for this climate oscillation are not known*". Although its origin is unclear, Cape Ferguson SST data appear to embed underlying, statistically significant, decadal-scale positive and negative phase-changes about the mean.

Low frequency implies a persistent multi-decadal signal possibly of generally wet *vs*. generally dry epochs. It has been found for example, that longer time-scale perturbations such as phase changes in the PDO/IDO moderate the magnitude and frequency of ENSO events, which has implications for the occurrence of floods, droughts and bushfires[1,2] (Figure 5).

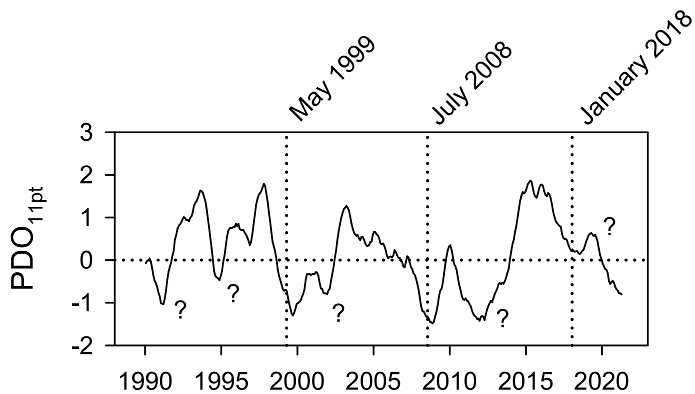

Figure 5. The 11-point moving average of the monthly Pacific Decadal Oscillation aligned with changepoints detected in sea-surface temperature residuals in May 1999, July 2008 and January 2018 (Figure3). Question marks (?) highlight that not all apparent PDO changepoints result in an SST response.

While it is beyond the scope of this Report to delve further into longer-term SST phase-changes, it is of interest to note similarities between changepoints detected in Figure 3 and abrupt reversals in the PDO index in Figure 5. Following a relatively dry period, it appears that the climate is entering a cool (moist) phase.

2.2 The seasonal progression of SST

The rate of cooling of Cape Ferguson SST from January to July is less than the rate of warming from July to December, which is a process known as hysteresis: 'dependence of the state of a system on its history'[3] (Figure 6). Thus, from the peak in January the waterbody and landscape to which it is connected loses heat relatively slowly and gains heat more quickly, quasi-linearly after August. The average SST increase of 1.03°C between November and December poses no threat to the survival of near-by reefs.

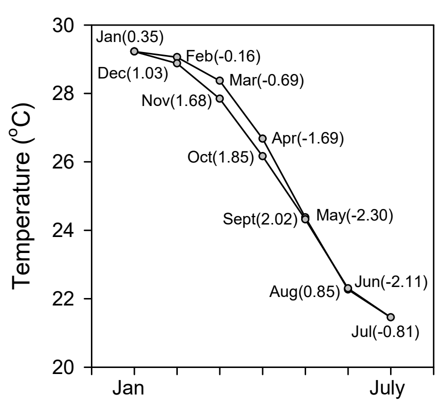

Figure 6. Hysteresis in cooling and warming trajectories of sea surface temperature at Cape Ferguson. Values in parenthesis show differences between successive months. Thus, SST in February is 0.16°C cooler than January. SST cools at a slower rate from January to May, than it warms from September.

3. SST dynamics of the Reef

3.1 The 1871 expedition

With support from the Royal Society and colonial governments, an expedition was mounted by Government astronomers from Melbourne and Sydney, aboard the steamer *Governor Blackall* out of

[1] See: Verdon, D. C., A. M. Wyatt, A. S. Kiem, and S. W. Franks (2004), Multidecadal variability of rainfall and streamflow: Eastern Australia, Water Resour. Res., 40, W10201, doi:10.1029/2004WR003234.

[2] Kiem, A. S., S. W. Franks, and G. Kuczera (2003), Multi-decadal variability of flood risk, Geophys. Res. Lett., 30(2), 1035, doi:10.1029/ 2002GL015992.

[3] https://en.wikipedia.org/wiki/Hysteresis#Rate-dependent

Sydney on 27 November 1871 to observe the total eclipse of the sun (Lomb, 2007[1]). Upon arrival in the vicinity of Cape Sidmouth near the top of Cape York (Latitude -13.42°), expeditioners set-up their telescopes and equipment on No. 6 Island of the Claremont Group on 6 December.

Commencing near Port Stephens NSW on 28 November, sea surface temperature "of the warm current setting south along the east coast of Australia"[2] was measured using bucket samples collected near the bow of the steamer each hour between 6 am and 6 pm. Data accompanied by notes, such as "Off Cape Byron" were transcribed into Excel, converted to Celsius and averaged in blocks corresponding to location information, with coordinates estimated using Google Earth Pro. Descriptions provided by Lomb, suggest temperatures in the vicinity of No. 6 Island (dubbed 'Eclipse Island' by the expedition; Latitude -13.49, Longitude 143.73) were for relatively shallow water, close to the coast. The ship travelled the same direction as the current on the return voyage, which commenced on 13 December. The 1871 data is the earliest consistently collected SST dataset around the Australian coast and has not been used before to objectively benchmark contemporary SST data. Original data tables and the derived summary dataset are provided as supplements to this Report (1871DataDoc.pdf, ExpeditionData.xlsx).

3.2 AIMS SST datasets

Loggers and weather stations deployed by AIMS along the GBR were searched to identify sites with reasonably long (>5-years) and complete records. High frequency (5, 10 or 30 minute) raw data was downloaded and processed using R into daily averages identified by dates and day of the year. Data were also aggregated into month by year, maxima, minima averages and monthly anomalies, which used to cursorily assess data fitness. The most northerly AIMS site with reasonably useful data was Thursday Island in Torres Strait, while the most southerly was North Solitary Island. (Most datasets were for sensors deployed at shallow depths (0-3 m), one was deployed at 24 m depth (Tydeman Cay), another at 7.4 m depth (19-138 Reef) and at 10.6 m depth at North Solitary Island.) While both the 1871 and the AIMS data spanned about 19 degrees of Latitude, AIMS data did not extend further south than North Solitary Island (Latitude -29.93° *vs*. -32.84 for Port Stephens) (Figure 7).

The final AIMS-SST dataset used in the study consisted of 27 sites (Figure 7). As data consisted of varying numbers of daily observations, over variable time periods, collected using a variety of dataloggers and sensors; sample averages were calculated across all observations at each site for day numbers corresponding to 1 November (day 306), 15 November (319), 04 December (338), 18 December (352), 01 January (01), 15 January (15), 01 February (32), 14 February (45), 1 March (60), 15 April (105) and the 15 July (196), August (227) September (258) and October (288) using lookup-tables in Excel (supplementary: AIMSdata.csv). Relationships between SST and latitude were analysed as second order polynomials.

3.3 Results

3.3.1 The 1871 dataset

As SST increased rapidly between late November and mid-December (Figure 6), initial analysis of 1871 data compared the pooled dataset with the same data segmented by voyages (up and back). Analysis of variance of pooled *vs*. segmented residual sums of squares found inclusion of a categorical variable for 'Up' and 'Back' significantly improved the polynomial fit. Thus, 'by-voyage' temperatures were significantly different ($P < 0.001$), especially north of Lady Elliott Island (Latitude -24.06°), which marks the southern extremity (S-limit) of the main body of the Reef (Figure 8).

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[1] https://eprints.usq.edu.au/29156/1/Paper%20(Lomb%20%2007).pdf

[2] Table XXVI (p. 56) in: H.C. Russell (1877). *Climate of New South Wales; Descriptive, Historical and Tabular*. Charles Potter, Acting Government Printer, Sydney.

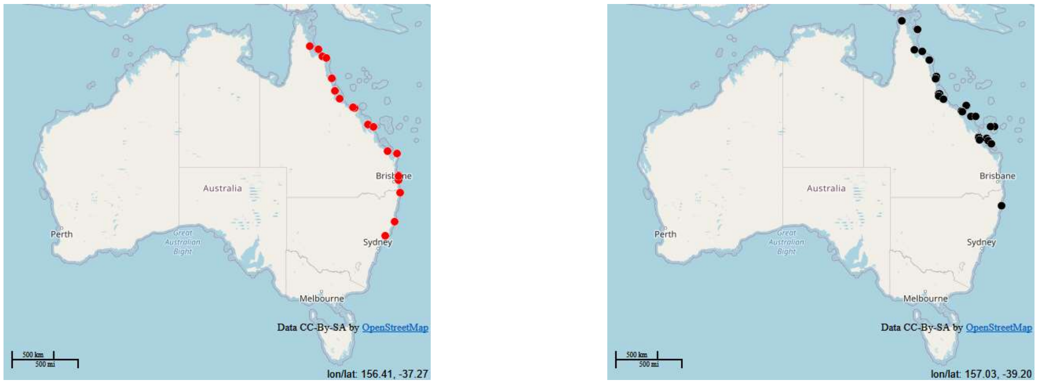


Figure 7. Sampling locations for the 25, 1871 expedition datapoints from Port Stephens, NSW to Cape Sidmouth Qld and return (left) and the location of the 27 datasets from AIMS (right). (Basemap courtesy of OpenStreetMap.)

Although they were sheltered by break-walls and located within 60 to 80 m of the shore, the magnitude of differences between average SST in November, December and January for ABSLMP gauges at Rosslyn Bay and Cape Ferguson were of the same order as between the 'Up' and 'Back' voyages in 1871 for those latitudes.

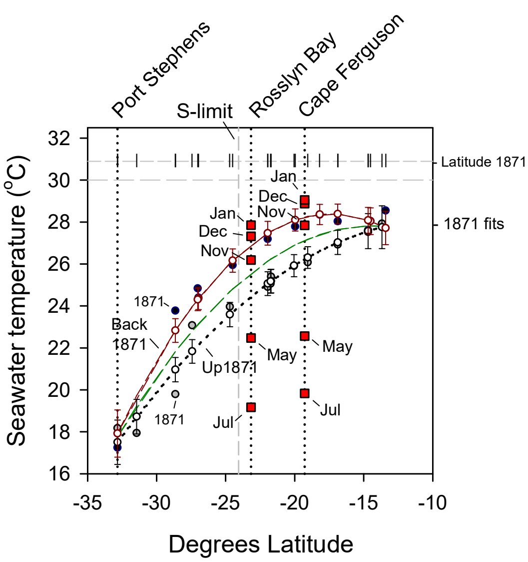


Figure 8. Relationships between 1871 bucket-sampled seawater temperature and Latitude. Separate regressions (grey circles 'Up' *vs.* black circles 'Back') explained significantly more variation in SST (R^2_{adj} = 0.967) than the pooled relationship (green dashed line; R^2_{adj} = 0.895). At that time of the year, differences between lines were greatest between Latitude -17° and about -24°, which marks the southern limit of the main body of the Reef (S-limit) and were least near Port Sidmouth and Port Stephens. Thus, while both series differed north to south by about 10°C, lines were not parallel. Vertical bars (top) show the latitudinal spacing of 1871 samples. Fitted values (circles) are shown with 95% confidence intervals. The annual temperature range between January, which is the warmest month, and July is 8.68°C at Rosslyn Bay and 9.39°C at Cape Ferguson.

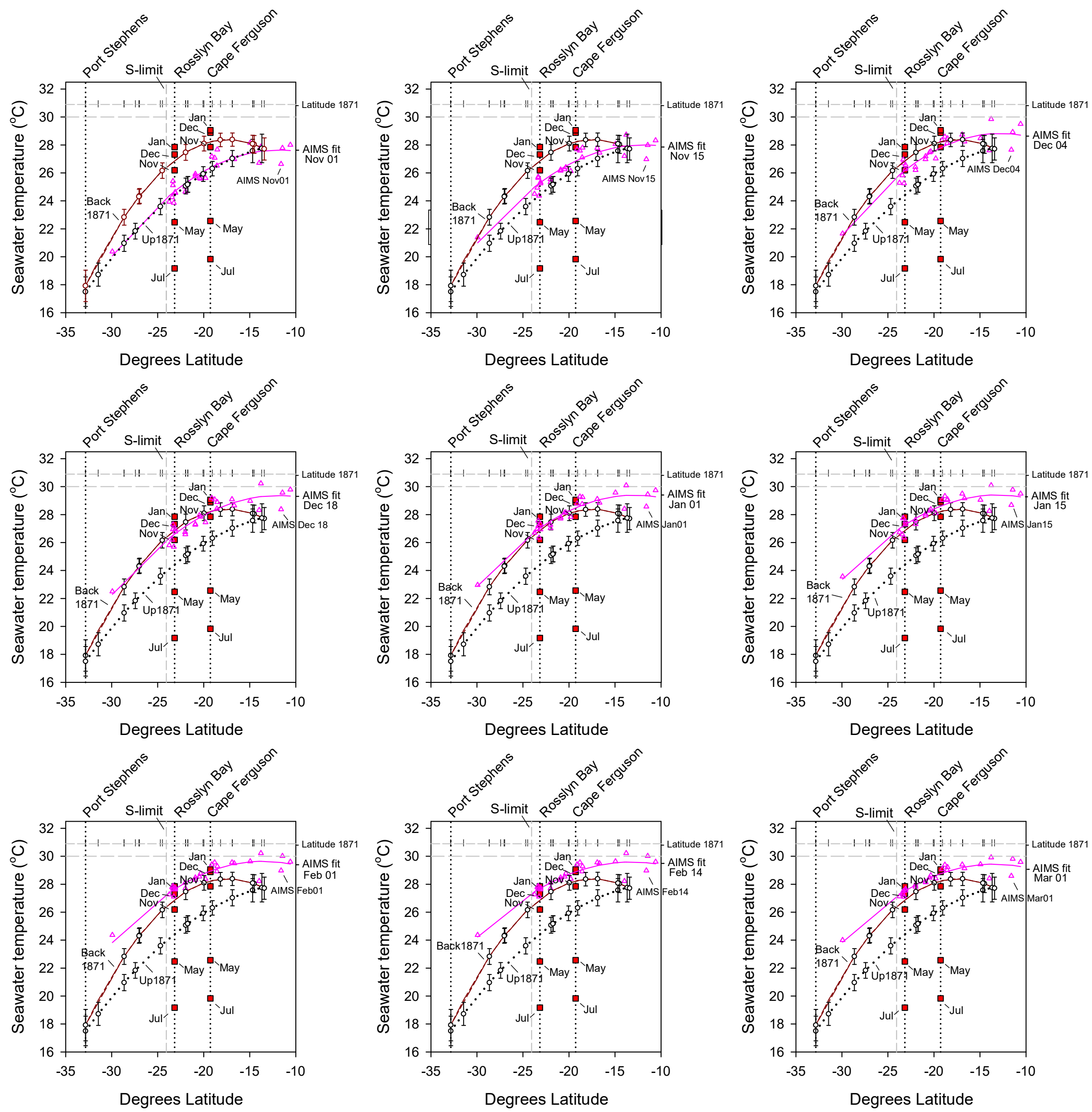
As the number of 1871 'Up' and 'Back' SST observations was relatively small (N = 13 and 12) and Latitude ranges were dissimilar, November through to January AIMS data (27 samples/interval) were not directly comparable. Nevertheless, the 1871 dataset provides an historic baseline with which to compare contemporary data particularly in the -10° to -24° Latitude band encompassing the Reef. (Note that 95% confidence intervals (CI) in Figure 8 define the 95% likelihood that the fitted relationship lies between the error bars; which is less than a prediction interval (PI), which is the uncertainty of a prediction for a specific Latitude.)

Although the ship was 'out of sight of land' north of Brisbane on the morning of 19 December, the *Governor Blackall* travelled about the same course each way and SST data were acquired using the same protocols and instrument. However, Latitude was estimated *post hoc*. Distance from the shore could not be estimated from information provided by the log.

3.3.2 Comparisons with AIMS and ABSLMP data

The historic 1871 series are compared with AIMS data from north to south along the Great Barrier Reef, and selected monthly averages for ABSLMP sites at Rosslyn Bay and Cape Ferguson in Figure 9. Due to the varying quality of AIMS data (incomplete, broken records; changes in loggers etc.) SST for Raine Island (the third most northerly site, data 1996-2012) was consistently cooler, while Wilkie Island (ranked fourth, 2004-2014) was consistently warmer than indicated by the relationship overall.

Despite spatial and temporal uncertainties in datasets, and within and between year variation in the behavior of the East Australian Current, the regression line for AIMS data for 01 and 15 November were within the confidence band of temperatures recorded during the 1871 'up' voyage from Port Stephens to Cape Sidmouth (Figure 9) and were therefore not different. Where they overlap (between the S-limit and Latitude -13°), AIMS data for 04 and 18 December, 01 January and 15 and 01 February, are also the same as temperatures observed on the return voyage from 13 to 24 December 1871.



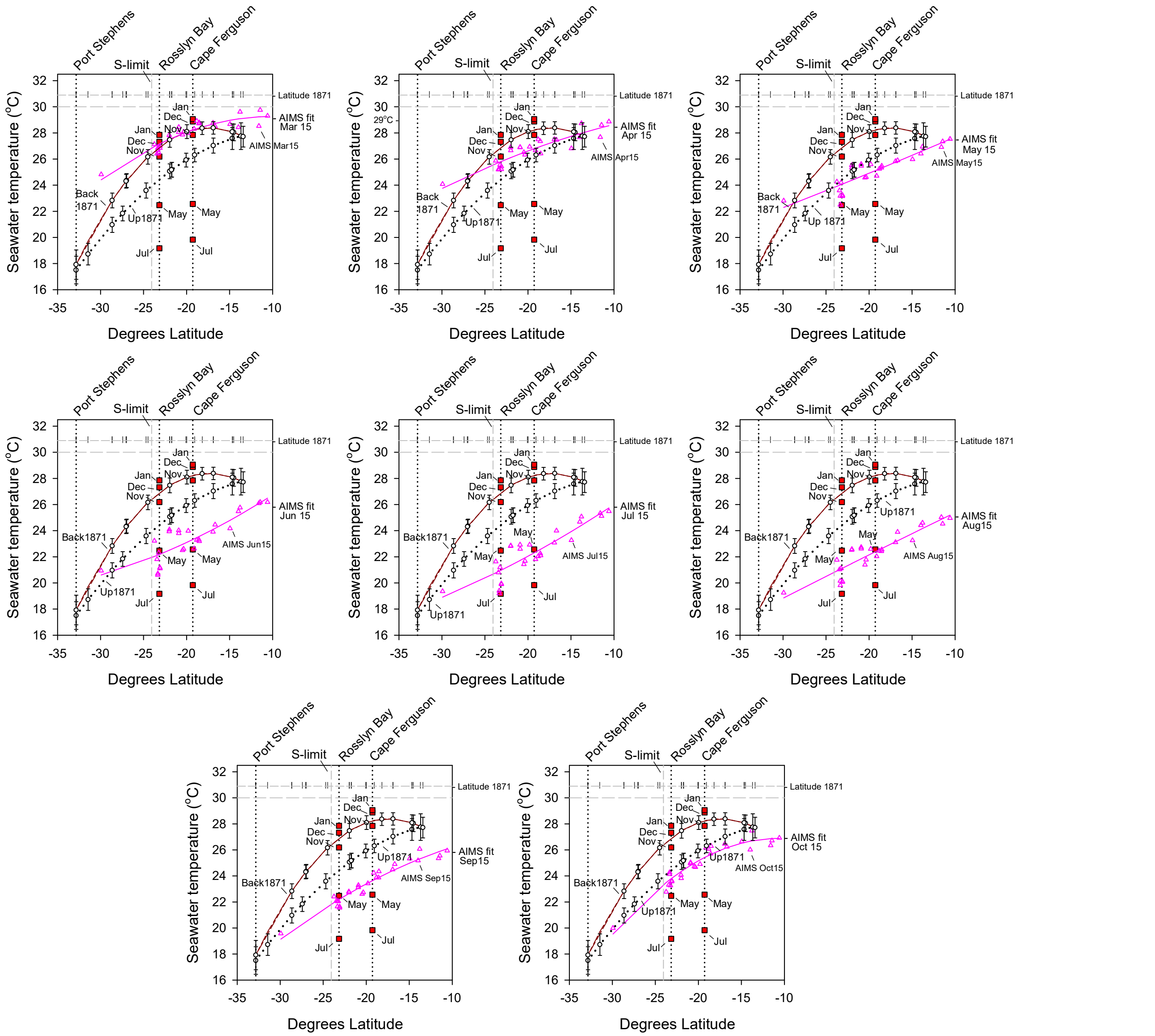


Figure 9. 'Up' and 'Back' sea surface temperature measured in 1871 (dotted and dashed) compared with data summarised from AIMS temperature loggers (pink, solid line), and ABSLMP gauges at Rosslyn Bay and Cape Ferguson. Bars represent 95% confidence intervals for the lines fitted to 1871 data. The vertical grey dashed line indicated the southern limit (S-limit) of the main body of the Reef (Lady Elliott Island, Latitude -24.06°)

Furthermore, toward its northern extremity (Bramble Cay, Latitude -9.08°, for which there is no useful AIMS data), while SST increases steadily from 01 November to mid-December, from then until March, SST remained between 29° and 30°C. The curvilinear response evidences an upper-limit to SST, which is rarely or only briefly exceeded.

3.4 Due diligence on the datasets

Statistically derived relationships are commonly evaluated by comparing observations (y) with predictions of the same datapoints (x) relative to a fitted 1:1 line with attention paid to non-linearity and outliers. Figure 10 shows that SST measured 'Up' and 'Back' by the 1871 expedition was closely predicted by

Latitude and except for the observation off Cape Byron, data fall close to the 1:1 line. Predictions were therefore statistically robust.

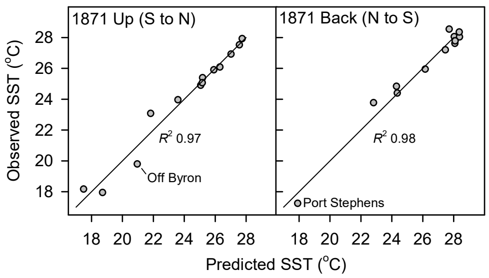


Figure 10. SST observations made by the 1871 expedition compared with statistically predicted values. The 1:1 line was determined by linear regression. Data off Cape Byron may have been contaminated by discharge from the Brunswick or Richmond rivers.

AIMS datasets were similarly robust with slope coefficients in the range from 0.96 to 1.19 and R^2 from 0.97 to 0.99. Figure 11 shows data for eight datasets spanning the length of the Reef, relative to a 1:1 line. Note there is some interference with upper-range values for Thursday Island, which is an inshore gauge.

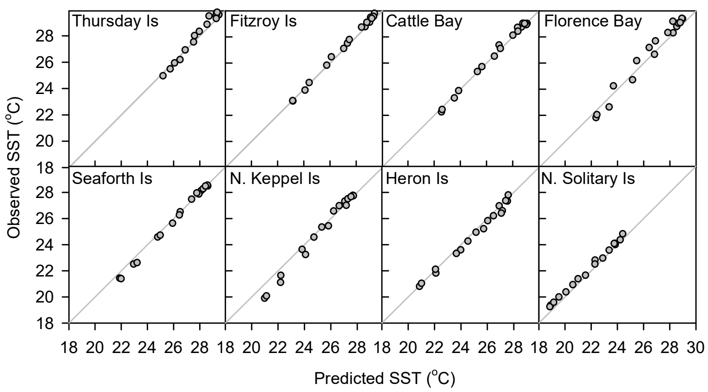


Figure 11. Observed SST (17 datapoints from 01 January to 18 December) vs. the same data predicted by latitude, for eight AIMS sites spanning the length of the Great Barrier Reef overlaid on a 1:1 line. Data for all sites showed close agreement.

3.5 Monthly temperature profiles (AIMS data)

Average monthly SST attains a plateau in late November that persists until the cooling phase commences in March thus lagging the summer Solstice by three months (Figure 12). Importantly, SST in the range 27°C to about 29°C from November to late March provides a five-month growing season, which combined with the minimum of ~ 20°C in July (North Keppel Island) defines the ecotone range of GBR ecosystems. Note for example, that while 10.6 m deep temperature at North Solitary Island closely tracked those at 1 m depth at North Keppel and Heron islands from April to July, SST at North Solitary Island is too cool from September to April (<24°C) for Reef ecosystems to establish and thrive.

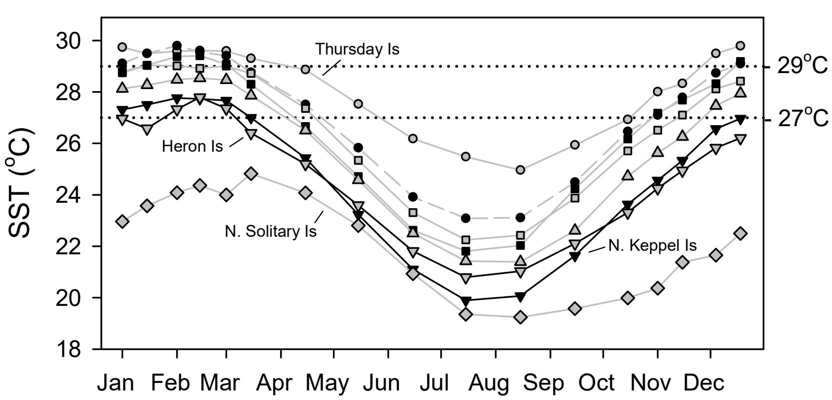


Figure 12. Temperature profiles for selected AIMS datasets: top, Thursday Island, then Fitzroy Island, Cattle Bay (Orpheus Island), Florence Island, Seaforth Island, North Keppel Island, Heron Island and North Solitary Island. Within the confines of the Reef, average SST ranges only 2°C (27° to 29°C) from late November to mid-March, which provides corals with an uninterrupted growing season of 4 to 5 months.

3.6 Trends in AIMS SST datasets

Although AIMS dataloggers and weather stations are reasonably well dispersed south of Cape Flattery and north of Heron Island, which takes in the main body of the Reef, most datasets are piecemeal and too short for determining medium or long term (20 to 30 year) trends. Data for Thursday Island for example, consists of one segment from May 1998 to October 2006, then several more patches of data each interspersed by years when no data was available (Figure 13). Piecemeal data for Arlington Reef overlap with data for nearby Fitzroy Island (Figure 14), but due to the difference in Latitude (-16.6891 vs. -16.9233) dataset-means are offset and therefore not useful for directly estimating trend.

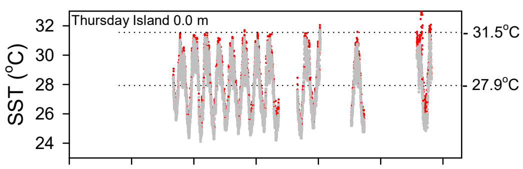


Figure 13. SST at Thursday Island, Torres Strait was measured by three or four dataloggers, with long breaks between. Relative to the dataset mean (27.9°C) and average daily absolute maximum temperature (31.5°C), no SST trends are evident. The gauge is located 50 m from shore on a busy wharf which is sheltered by surrounding islands.

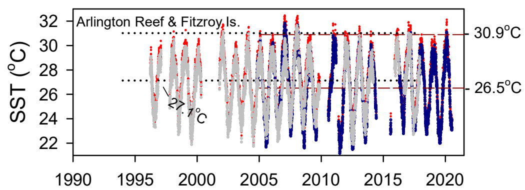


Figure 14. Data patched for Arlington Reef (March 1996 to February 2020; 2.4 m) and Fitzroy Island (two sites; March 1996 to February 2021, 3 m) (blue); and average daily maximum temperature for both sites (30.9°C, red dots). Differences are apparent between loggers and dataset means are offset by 0.6°C.

Use of several dataloggers and instruments at Geoffrey Bay, Magnetic Island (December 1992 to September 2011), which was not used in the study, patched with a more recent series from June 2016 to 2021 resulted in discontinuities and a spurious, seemingly negative trend (Figure 15).

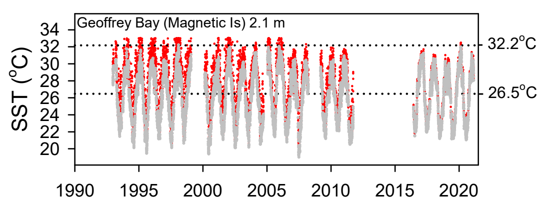


Figure 15. Four or more dataloggers were used at Geoffrey Bay, 170 m from the rocky shore of Magnetic Island, which caused the patched data to be discontinuous from January 1999, September 2004, January 2005, March 2009 with data from June 2016. The apparent cooling trend is spurious.

Inconsistent sampling, haphazard protocols and untimely maintenance also affect temporal comparability of same-site data. Early loggers sampled 48, 30-minute samples/day, others, 144, 10-minute samples/day, while more recent loggers sample at 288, 5-minute samples/day. Such changes in sampling and processing methods result in inhomogeneities that may invalidate naïvely determined trends. (More intense sampling generally results in higher numbers of spikes and extremes.)

Despite trend in sea-surface temperature being viewed as a threatening process that may 'catastrophically' impact on the long-term 'health' and survival of the Reef, AIMS operates too many sampling sites and too-few that are sufficiently-well maintained and serviced to provide reliable long-term data useful for critical studies. Even the ABSLMP temperature sensor located on the AIMS wharf at Cape Ferguson was off-line from October 2019 to May 2021 (19 months). It seems also that neither AIMS, nor other institutions involved in Reef research operate or host automatic weather stations (AWS) that collect the full suite of weather data as part of BoM's national network. Neither does BoM's Cape Ferguson weather station report daily maximum and minimum air temperatures needed to analyse temperature extremes. The manual site at the Cape Cleveland lighthouse (BoM ID 32005) closed in 1987 but was not replaced by an AWS, while the nearest BoM site at Townsville Airport is biased in other ways, including by undocumented site moves and changes[1]. Data acquired by off-the-shelf automatic weather stations, tide gauges and temperature loggers may not necessarily be of a sufficiently high standard for critical studies.

If the most pressing concern is that warming critically endangers the Reef, maintaining a well-distributed network of reliable sensors near its extremities should be accorded priority over deploying more loggers in areas where they are already present in numbers that cannot be serviced. Searching for data for specific purposes is also inefficient and time-wasting. A concise list that specifies the name, coordinates, depths, numbers of loggers deployed, start and end dates, and % completeness with links to datasets and metadata would considerably benefit on-going and future research.

Transect studies from beyond its extremities along the length of the Reef would generate more reliable data at fixed timepoints than dataloggers and weather stations with their problems of siting close to land and rocky headlands, within harbours and bays and closeness to wharf infrastructure, vessel movements etc. over which there is no control. Duplicating the timing and sampling method of the 1871 expedition over several years, and supplementing it year-about with an additional cruise during winter would provide unambiguous baseline data relating to warming and cooling cycles and their potential effect on Reef ecosystems. The haphazard, inefficient Reef sampling program is in need of review.

3.7 Dynamic changes in SST

While Figure 9 summarises month by month changes in SST; and Figure 12 shows monthly averages and ranges for re-sampled AIMS data, the third dimension in the behavior of SST, is its rate of change with respect to Latitude (i.e., ΔSST/ΔLatitude) (Figures 16, 17 and 18).

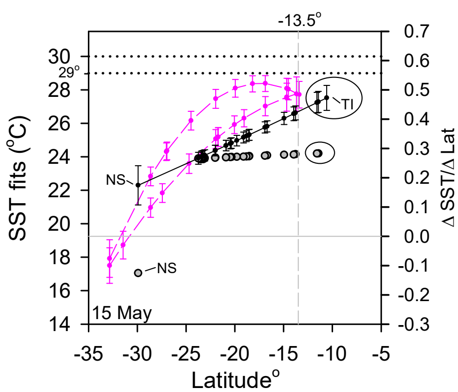


Figure 16. Fitted polynomial regressions (±95% CI) for the 'up' and 'back' voyage in 1871 (pink) and averaged AIMS data for 15 May (black line and symbols; all left axis), and the rate of change of AIMS data (ΔSST/ΔLatitude) (right axis; grey circles). Lagging the summer solstice, SST had cooled appreciably by 15 May, linearly with Latitude (27.5°C at Thursday Island (TI) *vs*. 23.9°C at Boult Reef (-23.75°), but it was still as warm at Heron Island as it was in late November 1871 (about 24°C). The rate of change was almost constant (0.26-0.28°C). Possibly due to a changed ocean circulation pattern data for North Solitary Island 730 km south (NS) was atypical (cooler than the Reef, but warmer per unit Latitude at that time).

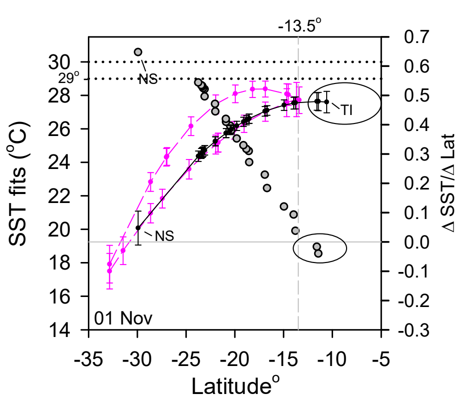


Figure 17. The warming cycle commences in September, strengthens through October and by 01 November AIMS SST directly overlay late November 1871 data. Closer to the equator, the rate of increase in SST was least (circled) (i.e., as SST increased, ΔSST/ΔLatitude declined) and the SST curve reached an asymptote where ΔSST/ΔLatitude was equal to or less than zero, corresponding to 27.6°C at Latitude -13.5°. Due to the asymptote, the rate of warming decreased to become negative north of -13.5° Latitude (data for Thursday Island, Raine Island and Wallace Islet are circled).

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[1] https://www.bomwatch.com.au/data-quality/climate-of-the-great-barrier-reef-queensland-climate-change-at-townsville-abstract-and-case-study/

At Thursday Island, solar exposure (SE) reaches a maximum in October (24.9MJ/m^2/day), but due to high humidity and an average of 21.5 wet days it declines to a minimum of 18.0 MJ/m^2/day at the height of summer in January. Maximum temperature, which is highest in November (31.2°C), remains around 29.0°C for six months, from January to May. In contrast, near the Reef's southern extremity off Gladstone (Latitude -23.84°), solar exposure declines from 25.3 MJ/m^2/day in November to a minimum of 13.6 MJ/m^2/day in June, and Tmax from 30.8°C in January to 23.2°C in July. Thus, there is a considerable gradient and a change in the behaviour of the general climate that should frame the debate about the Reef's adaptive range and possible future threats. Although rainfall is summer dominant throughout, the climate is not monsoonal except in the far north.

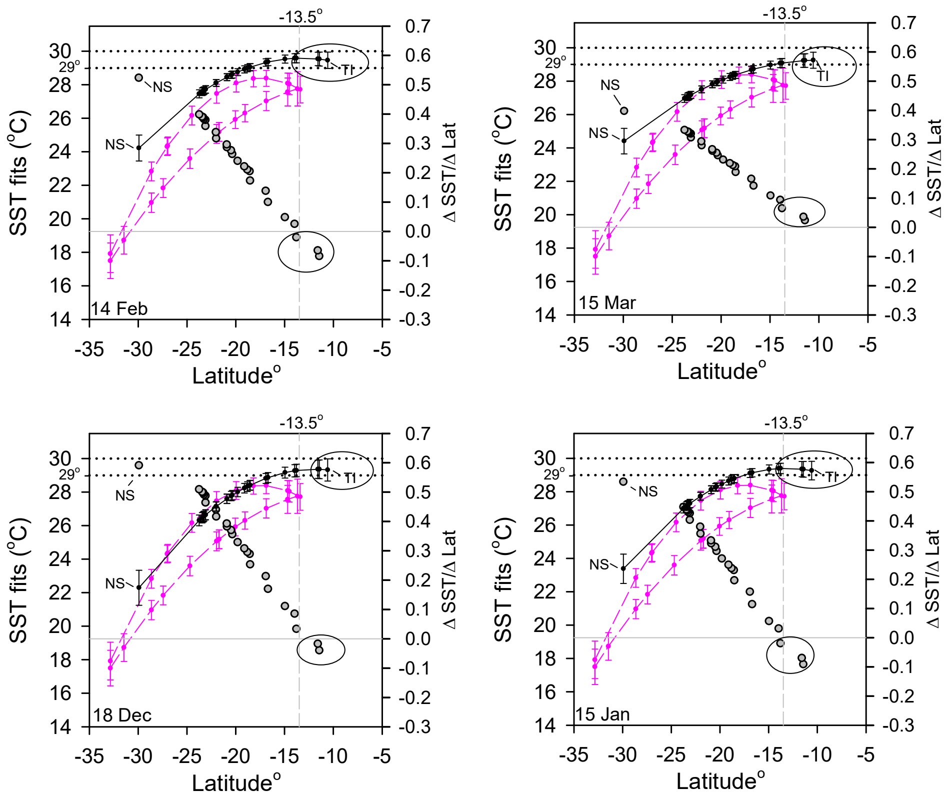

Figure 18. December to March temperature profiles show that in the north, the potential for 'runaway' warming is controlled by the monsoon (cloudiness, convection and rainfall), while in the south cooling via convection of latent heat on warm sunny days and advection to the cool, generally dry souteasterly airstream, hold SST within close bounds. From November through to March, AIMS SST is not significantly different (confidence intervals overlap) to data collected on the return journey from Cape Sidmouth to Port Stephens in mid-December 1871. There is therefore no evidence that AIMS data are appreciably warmer. Note that between mid-December and mid-January, which is the warmest month, the asymptote of the temperature curve moves south (to -13.5° Latitude), consequently ΔSST/ΔLatitude becomes less than zero. That self-regulating behaviour maintains the temperature of the tropical ocean within the bandwidth of 29° to <30°C making it impossible for global warming to influence SST.

At Latitude -13.5°, which was the warmest point along the transect, maximum predicted SST (29.64°C $\pm_{PI}$ 1.12°C) occurred in late January to early February, the minimum occurred in mid-August (24.26°C $\pm_{PI}$ 1.47°C), SST increased to mid-November (27.96°C $\pm_{PI}$ 1.1°C) after which the cycle repeated. The interannual range was therefore about 5.4°C.

4. Discussion

The consortium of parties that undertake research or have an interest in the Great Barrier Reef loudly claim that survival of the Reef is critically endangered by warming of the climate due to anthropogenic factors.

For example, the Great Barrier Reef Foundation asserts that "climate change is the greatest threat facing the Reef and a challenge we must all tackle together …. rising water temperatures, poorer water quality … pollution … perfect storms …" EarthWatch says "Save the Reef and oceans … the Reef is facing annihilation". The Australian Museum poses the question "Can the Great Barrier Reef survive climate change?"; while Greenpeace claims "… coral reefs could soon be gone forever … deteriorating at an alarming rate … lost 50% of its corals …" From WWF "Coral bleaching is the result of global warming". The Climate Council reports: "Catastrophic mortality confirmed on GBR … unprecedented loss", with Councilor Professor Will Steffen saying that "Australia's woefully inadequate climate and energy policy had led to the nation's greenhouse gas pollution levels reaching disappointing new heights …".

However, average sea surface temperatures are no warmer in recent years than they were in November and December 150 years earlier in 1871 (Figure 9). Consistent with previous research by Richard Willoughby[1], who found that the open ocean SST is limited to 32°C and regulates to an upper limit of 30°C, Figures 15 to 18, show that as solar radiation increases in summer, SST north of Latitude -13.5° is cooled by the monsoon and remains in the range of 20°C to 30°C. The Southern Equatorial Current which splits to form the North Queensland current and the south-flowing East Australian Current which dissipates into the Tasman Sea, is cooled continuously by convection, long-wave re-radiation to space by towering clouds, cool rainfall and the formation of reflective residual cirrus 'ice-clouds'. These processes maintain SST within close limits that rarely (and only transiently) exceed 30°C.

So how did science come to this?

4.1 Background

Data about Australia's climate was collected to describe the weather, not to measure trend and change. Consequently, the quality and documentation (metadata) of weather data is unlikely to be fit for the purpose of estimating long-term changes. A versatile physically-based replicable framework for undertaking due diligence on data is therefore of paramount importance.

Commencing with a case-study of the BoM temperature dataset for Gladstone Radar (BoM ID 39123), which outlined such a framework for maximum temperature data; studies were published by https://www.bomwatch.com.au/ of ACORN-SAT (Australian Climate Observations Network – Surface Air Temperature) weather stations spanning the Reef at Cairns, Townsville and Rockhampton. Investigations included detailed research of documents etc. held by the National Library and National Archives of Australia (NLA and NAA) including aerial photographs, WWII Royal Australian Air Force (RAAF) files, aerodrome maps and surveys; Queensland government aerial photographs; newspaper reports of the day; and documents held by the Civil Aviation Historical Society's Museum at Essendon Fields, Melbourne. 'World leading experts' and more recently the ACORN-SAT Technical Advisory Forum of 'leading scientists and statisticians' who peer-reviewed the Bureau's methods sidestepped an essential question, which is: *whether trends and changes in data are due to site and instrument changes or the climate* (see http://www.bom.gov.au /climate/change/acorn-sat/documents/About_ACORN-SAT.pdf).

Investigations by BomWatch found that:

- Coordinates of original meteorological enclosures were unknown (or known but not stated in metadata) and despite repeated claims by acclaimed Australian climate scientists that site-histories had been well-researched it was not the case. Bureau scientists and peer reviewers **failed to find things because they did not look**. In particular the Bureau's Garbutt (Townsville) Instrument file, which had been scanned by NAA and was available online, directly contradicted claims that the

[1] https://www.bomwatch.com.au/ocean-temperature-limit/

Bureau's data management procedures and processes were trustworthy and amongst the best in the world.

- Trends in temperature at Cairns, Townsville and Rockhampton, were created by the process of data homogenisation, which selectively ignored the effect of site changes on data (or corrected for changes that made no difference) to imply they were due to the climate. In particular, site relocations in the 1950s to 1970, introduction of automatic weather stations which became primary instruments after September 1996, the staged replacement of 230-litre Stevenson screens with 60-litre ones which accelerated after 2000, reductions in site maintenance as staff were withdrawn and the use of herbicides instead of regular mowing in the vicinity of where temperature was measured, created spurious trends in datasets.
- BomWatch investigations (https://www.bomwatch.com.au/climate-of-great-barrier-reef/) showed that when unbiasedly corrected for site and instrument changes, no trend remained that could be attributed to the climate. So, since weather observations commenced at former Aeradio sites around 1938, within statistical limits (generally P =0.05) there is no evidence that terrestrial temperatures have increased in the vicinity of the Great Barrier Reef. Data does not support repeated and increasingly noisy assertions by the Reef 2050 Plan Independent Expert Panel, and other committees that the climate is warming and that catastrophe is imminent.

4.2 Sea-surface temperature changes

By distinguishing between variables that cause variation ***IN*** SST data, from those that impact ***ON*** the data-stream, research reported in this paper evaluated the claim that SST is increasing, or has increased over recent decades to levels that threaten survival of GBR ecosystems. After removing non-trending seasonal cycles in data for the ABSLMP site at Cape Ferguson, where temperatures have been measured since September 1991, terrestrial Tmax and barometric pressure (hPa) were found to explain about 40% of variation in mean monthly SST. Also, an underlying PDO-like signal that explained a further 11% of variation (partial R^2) that could not be explained by Tmax and barometric pressure was detected in residuals. Interaction of the fixed gauge in the confines of the bay with the passing East Australian Current for which no parallel data was available, contributed an unknown proportion of the remaining variation in SST.

The important point arising from the Cape Ferguson study was that water temperature close to shore was greatly influenced by heat exchanges with the landscape, which may cause bias especially during dry summer months when temperatures are generally above average. Furthermore, over the 30-years of record, accounting for terrestrial temperature, barometric pressure and PDO-like step-changes left no SST trend that could be attributable to warming or any other factor. Relatively slow SST cooling after February and higher rates of warming after August resulted in hysteresis –lagged responses to changing seasonal conditions (Figure 8). As the cycle recurs, it follows that Reef ecosystems are highly adapted to SST differences exceeding ±>1.5°C/month during both cooling and warming phases. The coral bleaching question cannot therefore be related to absolute changes in SST less than that magnitude.

4.3 The 1871 expedition and AIMS datasets

The November-December 1871 expedition dataset has not been used before to objectively baseline changes in SST along the Reef. Volumes of water entering the Reef lagoon from the north must be balanced by the sum of direct evaporation and volumes exiting to the Tasman Sea in the south. Thus, as the East Australian Current cools from its source southwards along the eastern seaboard, SST behavior is a simple function of Latitude (Figure 9). Consistent with SST increasing at Cape Ferguson between November and December, data measured by expeditioners on the 'Up' voyage in late-November was significantly cooler than measured 2-weeks later on their return commencing 13 December, particularly north of Latitude -24° which marks the southern extremity of the body of the Reef off Gladstone (-23.86°). While the East Australian Current warms from October to December, curvature of the relationship indicates that north of about Townsville (Latitude -19.26°), the average rate of increase in SST from spring to early summer becomes limited by feedback processes, otherwise, SST would be linearly warm to the Equator.

The method of determining day-of-year averages across AIMS datasets overcame deficiencies in data availability (broken records), quality (deployment of loggers that used different sampling intervals and averaging algorithms), length of record (which was highly variable) and also dispersion (AIMS data was not well dispersed north of Cape Flattery or south of Lady Elliot Island). As observed and predicted values were closely aligned 1:1 (Figure 11) and Latitude explained >77% of variation in AIMS SST in winter and >87% during warmer months, data derived by sampling was robust and fit for the purpose of examining time evolution of SST along the length of the Reef.

The question of whether mean monthly SST is increasing, is best addressed by considering the behavior of the system overall than focusing on particular SST values or particular sites that may be affected by *in situ* contamination by terrestrial temperatures etc., and problems in the data. As regression efficiently smooths irregularities, discussion relating to Figure 9 focusses on statistical relationships between SST and Latitude over time.

The curvilinear response from November to March shows that for a given Latitude SST cannot increase beyond that indicated by data for the warmest month. Along the transect, ceiling SST is predicted to occur at Latitude -13.5°, which by coincidence is about the Latitude of Cape Sidmouth (-13.49°) where the expeditioners established their observatory in 1871, and also approximately where the South Equatorial Current splits into the north-flowing North Queensland Current and the East Australian Current which flows south. Although SST is predicted to become slightly cooler further north, over the Latitude range differences are immaterial. SST at Latitude -13.5 was predicted to reduce from 29.64°C ($\pm_{PI}$ 1.12°C) in late-January to early-February to 29.11°C ($\pm_{PI}$ 0.91) by mid-March then 24.52°C ($\pm_{PI}$ 1.9°C) by 15 July. Minimum SST (24.26°C $\pm_{PI}$ 1.47°C) occurred in mid-August before increasing again to 27.96°C ($\pm_{PI}$ 1.1°C) by mid-November after which the cycle repeats. The interannual range at Latitude -13.5 was therefore 5.38°C, which is not much different to 6.93°C at Heron Island (20.87°C in mid-July, 27.80°C in mid-February).

Seasonal variation is made clearer in Figure 12, which benchmarks the adaptive range of Reef ecosystems as being within an SST bandwidth of 27°C to >29°C and mostly less than 30°C, for four to five months, and a minimum in winter (July to September) of >20°C. Although coral reefs occur south of Gladstone in Moreton Bay (Latitude *c*. -27°) where they were extensively dredged for cement production from 1937 to 1995, there were no useful AIMS temperature datasets south of Lady Musgrave Reef (where SST ranged from about 20°C to 28°C). Although limited by available data, it seems reef ecosystems have apparently not established in profusion outside those bandwidths. Further, due to the continent blocking and directing the warm sub-equatorial current south, Australia's northeast coast may be the only region on the planet where reefs could thrive over a continuous band across *c*. 24° Latitude south (or north) of the equator. In that respect the Reef is indeed unique.

Consistent with the aforementioned study by Richard Willoughby study on Limits to Ocean warming, the water cycle operates as a self-regulating heat-pump that catapults moisture high into the atmosphere to form persistent cloud that reflects or rejects incoming solar energy during the monsoon and thereby limits input of warm waters to the East Australian Current. Although variable through the seasons, depending on transmissivity of the atmosphere, energy available at the surface on a particular day is finite. During the dry-season warm cloudless days increase evaporation (E_A), which removes heat from the surface of the ocean at the rate of 2.45MJ/kg of water evaporated, resulting in cooling, while humidity and cloudiness reduce incoming solar radiation. As explained by Richard Willoughby there is an infinite amount of ocean-water available to partition surface energy fluxes in summer between sensible heat, which increases SST and E_A, which, with its embedded latent heat, is removed by convection back into the atmosphere, forms clouds that emit radiation to space, precipitates, which is cooling leaving residual high-level ice-clouds (cirrus) that re-radiate incoming solar radiation. The mechanism, which dominates atmospheric processes when the surface temperature is 28C or higher is physically based, uncomplicated, easily understood, operates north of Latitude -13.5°, and maintains the temperature of the earth within seasonally cycling homeostatic limits. AIMS SST data shows no evidence that the process has broken-down or is likely to break down in the future.

Given the difficulty of obtaining accurate uncontaminated data over a sufficiently long period; the vastness of the ocean which is constantly moving; the interconnectedness of solar energy input, the water cycle and cloud feed-backs; and geographic factors such as Latitude, Longitude (distance from shore), depth of water and volume and rate of flow down the east coast of Australia, the chance of detecting a minuscule average SST increase of 0.8°C, which is much less than the error with which it could be measured; then attributing that to atmospheric CO_2 increasing from 278 ppm (0.028%) to 400 ppm (0.042%) in a century; then in-turn blaming that on the consumption of fossil fuels is an unlikely combination of scenarios. There is also no evidence within the bounds of statistical probability, that SST measured by the expeditioners in 1871 using a transect of bucket samples from Port Stephens to Cape Sidmouth in late November and a second transect along the same route 2-weeks later could be regarded as different to the inefficient, haphazard and expensive sampling program operated by AIMS since the 1990s. There is no evidence from AIMS data that the Great Barrier Reef is threatened by global warming. As no data agrees with them, the models driving all the speculations are wrong.

While it is possible that water temperature in the vicinity of Cape Sidmouth was unduly affected by uncontrolled factors including proximity to the shore, depth of water and discharge from the Lockhart River; anchored by that point, Latitude explained 96.9% of the variation in SST for the return voyage to Port Stephens. For composite AIMS datasets, which ranged further north and east, R^2_{adj} varied from: 0.841 for 4 December; 0.850 for 18 December; 0.800 for 1 January; 0.759 for 15 January; and 0.821 for 1 February. Precision of the 1871 dataset was thus comparable (or more-so) with the composite AIMS dataset used in the study.

5. Conclusions

- SST measured close to shore such as at Cape Ferguson and Rosslyn Bay near Yepoon (which has not been analysed in detail here), are biased by heat exchanges with the landscape especially during periods of low summer rainfall when maximum temperature (Tmax) is axiomatically higher.
- At Cape Ferguson SST cooled more slowly from its peak in January to July than it warmed from August to December. Great Barrier Reef ecosystems are therefore adapted to the 8.1°C interannual cycle and average month-to-month SST changes of 1°C to 2°C. Removing the cycle, which shows no trend, and accounting for the significant effect of terrestrial Tmax on SST, left no trend or change in SST attributable to any other factor. There is therefore no evidence that SST has warmed since records commenced at Cape Ferguson in September 1991.
- The Australian Institute of Marine Science (AIMS) SST data is patchy, poorly dispersed towards the extremities of the Reef and not useful for determining long-term trends. Selected day-of-year averages for 27 sites extending from Thursday Island above Cape York to North Solitary Island in the south showed the adaptive range of Reef ecosystems was within the bandwidth of 27°C to >29°C mostly <30°C for four to five months and >20°C in winter (July to September). Warmest temperatures were predicted to occur at Latitude -13.5° in late January with SST cooling slightly northwards.
- The Southern Equatorial Current which on reaching the Great Barrier Reef splits to form the North Queensland current and the East Australian Current which dissipates south into the Tasman Sea, is cooled continuously by convection, long-wave re-radiation to space by towering clouds, cool rainfall and the formation of reflective residual cirrus 'ice-clouds'. These processes maintain SST within close limits that rarely or only transiently exceed 30°C.

- No difference was found between sea surface temperature measured between Port Stephens and Cape Sidmouth by astronomers from Melbourne and Sydney using bucket samples in November and December 1871 and AIMS data sampled at those times.
- There is no evidence that supports claims by AIMS, associated entities and lobby groups including WWF and the Climate Council that sea surface temperature has increased by an unremarkable 0.8°C, and that continued warming is likely to threaten survival of the Great Barrier Reef.

Dr. Bill Johnston

v. 06 October 2021

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Author's note: Although this draft paper has been carefully researched and uses statistical tools, data and other evidence that is available in the public domain, no responsibility is accepted for errors of fact arising from the scarcity of information or photographs etc.

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http://www.bomwatch.com.au/ 19 pp.