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Sea Surface Temperatures on the Great Barrier Reef: a Contribution to the Study of Coral Bleaching

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JM Lough Australian Institute of Marine Science





GREAT BARRIER REEF MARINE PARK AUTHORITY



A REPORT TO THE GREAT BARRIER REEF MARINE PARK AUTHORITY

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SUMMARY

The extensive coral bleaching event on the Great Barrier Reef (GBR) in early 1998 highlighted the possible causative role of elevated sea surface temperatures (SSTs) and links with El Niño-Southern Oscillation (ENSO) events. Three questions related to the 1998 event and SSTs off the northeast Australian coast are addressed in this report:

- How unusual were SSTs in 1998?
- ♦ Was this a typical ENSO signal on the GBR?
- ♦ Is the SST climate of the GBR changing?

Three data sets are used to examine SST variations off northeast Australia: *in situ* data loggers, blended satellite data and "ships of opportunity" data.

Agreement between absolute *in situ* SST data logger and blended satellite observations varies with location and season. Relative temporal variations in the two data sets show a significant level of agreement. Agreement between the two data sets increases with averaging over longer time periods (eg monthly is better than weekly). Agreement between the blended satellite and "ships of opportunity" data is reasonably good. Systematic biases are, however, evident, and are possibly related to common data used to "tune" the satellite data and seasonal and latitudinal variations in cloud amount. Overall, however, the level of agreement between the three different SST data sets is surprisingly good.

Evidence from the daily SST data loggers located on reefs suggests that 1998 was unusual both in the number of days SSTs exceeded a particular threshold and also in the intensity of the SST anomalies above the threshold (ie number of degree days). Evidence from the blended satellite data indicates that the maximum monthly mean SSTs in early 1998 were the most extreme during the period 1982 to 1998. The next warmest years were 1987 and 1982. Evidence from the "ships of opportunity" data places 1987 as the most extreme year within the period 1903 to 1994. This, combined with the satellite data, suggests that 1998 was the most extreme year in the past 95 years on the GBR.

During a typical ENSO event SSTs on the GBR tend to be cooler than normal in the winter season and warmer than normal in the following summer. SST anomalies on the GBR in 1997-98 were qualitatively similar to typical ENSO events.

Annual and seasonal average and maximum monthly mean SSTs have increased significantly off the northeast Australian coast from 1903 to 1994. These warming trends are evident along the GBR but are greatest to the south of the GBR. These variations match warming over the same time period in Queensland average and minimum temperatures and the Southern Hemisphere combined land and marine temperatures.

It is concluded that:

- SSTs on the GBR in early 1998 were the warmest in the past 95 years of instrumental records.
- SST anomalies on the GBR in 1997-98 were typical of ENSO events.
- SSTs on the GBR have significantly warmed over the present century.

INTRODUCTION

The extensive coral bleaching event on the Great Barrier Reef (GBR) in early 1998 focussed attention on the role that unusually high sea surface temperatures (SSTs) might play in triggering coral bleaching. 1997-1998 also witnessed significant coral bleaching events at many reef sites around the world (Wilkinson, 1998; Berkelmans and Oliver, in press). A link was made between unusually high summer SSTs and the 1997-99 El Niño-Southern Oscillation (ENSO) event (Wilkinson *et al.*, in press). As a contribution to the study of coral bleaching events on the GBR, this report addresses the following questions:

- 1. How unusual were the SST anomalies of 1997-1998?
- 2. What is the average SST signal on the GBR associated with ENSO and anti-ENSO events and was the signal observed during 1997-98 consistent with this?
- 3. Is there evidence that the SST "climate" of the GBR region is changing? ie is the frequency of conditions that might be associated with coral bleaching increasing?

These questions are addressed using three readily available SST data sets:

- Great Barrier Reef Marine Park Authority (GBRMPA) *in situ* SST logger data recorded halfhourly for various sites along the GBR from the mid-1990s.
- Integrated Global Ocean Services System (IGOSS)-NMC blended satellite data available weekly and monthly from November 1981 to date for 1°-latitude by longitude square resolution
- Global Ocean Surface Temperature Atlas Plus (GOSTAplus) "ships of opportunity" data available monthly from 1903 to 1994 for 1°-latitude by longitude square resolution.

Each of these data sets has its advantages; the GBRMPA data loggers are recording SST at high temporal resolution at reef sites, the IGOSS blended satellite data is updated rapidly and provides a large-scale, global perspective and the GOSTA "ships of opportunity" data provide an historical perspective extending back to the start of the 20th century.

Comparisons are first made between the different SST data sets: GBRMPA and IGOSS, IGOSS and GOSTA. Analyses are then presented for 1°-latitude bands along the northeast Australian coast from 10.5-29.5°S. The latitudinal bands from 10.5-24.5°S encompass the GBR. The average SST "signal" associated with ENSO and anti-ENSO events is determined. Variations in summer warm season extremes and annual and seasonal average SSTs are then examined for evidence of significant trends from 1903 to 1994. Comparisons are then made with other regional climatic indices over the present century.

DATA

GBRMPA in situ SST data

The Great Barrier Reef Marine Park Authority (GBRMPA) started a long-term SST monitoring program on the GBR in the mid-1990s. Data are obtained from *in situ* data loggers at various reef sites. The loggers record SSTs every half-hour and the data are downloaded every 6-12 months (see <u>www.gbrmpa.gov.au/seatemp/</u>). Daily average, daily maximum and daily minimum SSTs were obtained for eight sites (Figure 1; Table 1; Ray Berkelmans, GBRMPA, pers. comm. October 1998). The choice of these sites was based on 1) the record being available through early 1998, and 2) the record being continuous over more than two years. For comparison with the IGOSS data, the daily SSTs were averaged over the same weeks (Sunday to Saturday) as the blended satellite data.

IGOSS-NMC SST data

Weekly and monthly SSTs were obtained for 1°-latitude by longitude squares in the vicinity of the GBR from the IGOSS-NMC data set (see <u>http://ingrid.ldeo.columbia.edu/)</u>. These data are



Figure 1. Location map showing 1°-latitude oceanic "boxes" for GOSTA and IGOSS SST data and sites of GBRMPA SST loggers used in this report.

available from November 1981 to date (the data are updated by about the second week of each month). These data are SST fields blended from ship, buoy and bias-corrected satellite data based on optimum interpolation (see Reynolds and Smith, 1994). For the period from 1981-1989, the *in situ* data were taken from the Comprehensive Ocean Atmosphere Data Set (COADS; based primarily on historical reports from "ships of opportunity", see Woodruff *et al.*, 1993). For the period from 1990 to present the *in situ* data are from radio messages on the Global Telecommunication System.

Comparisons between the IGOSS and GBRMPA data were based on the 1° square closest to the data logger site. For the comparisons with the GOSTA data and subsequent analyses, the IGOSS 1° square data were averaged for 1°-latitude by 2-4° longitude boxes along the northeast Australian coast from 10.5°S to 29.5°S (see Figure 1). It should be noted that both the IGOSS and GOSTAPlus 1° SST data contain some element of spatial smoothing so that adjacent squares will not be independent.

GOSTA SST data

Monthly SSTs were obtained for 1°-latitude by longitude squares from the GOSTAPlus data set (Version GIST 2.2) produced by the United Kingdom Meteorological Office in collaboration with the Massachusetts Institute of Technology and the Physical Oceanography Distributed Active Archive Center (data freely available on CD-ROM on application to the UKMO). Monthly data are available from 1903 through 1994. These data are averages of SST measurements by month and square made by "ships of opportunity", supplemented in recent years by Automatic Weather Stations and buoys (see Bottomley *et al.*, 1990). Instrumental SST measurements from "ships of opportunity" are affected by changes in measurement procedures over the 20th century (basically a change from uninsulated canvas or metal buckets to either insulated buckets or engine-intake or hull-sensor thermometers). The latter can record SSTs warmer than insulated bucket measurements resulting in a spurious worldwide increase in SSTs over the present century. The GOSTAplus SST data used here have been corrected for these measurement (and other) sources of error (see Folland and Parker, 1995). Monthly SST data were averaged for the same 20 boxes as the IGOSS data (see Figure 1).

Site	Start date	End Date	# days		Daily Average	Daily Maximum	Daily Minimum
Coconut Beach	20 Jul	6 Sep		Mean	28.3	29.0	27.7
Reef Flat	1996	1998	364	Maximum	31.8	32.7	31.2
				Date of maximum	14 Feb 1998	14 Feb 1998	15 Feb 1998
Myrmidon Reef	14 Apr	2 May		Mean	27.6	28.1	27.2
Flat	1995	1998	547	Maximum	29.9	30.7	29.4
				Date of maximum	20 Feb 1998	19 Feb 1998	16 Feb 1998
Pelorus Is	6 Nov	26 Apr		Mean	27.9	28.9	27.1
Reef Flat	1993	1998	875	Maximum	31.3	32.6	30.7
				Date of maximum	30 Jan 1998	28 Jan 1998	30 Jan 1998
Pelorus Is	3 Jan	30 Apr		Mean	27.8	28.1	27.5
Reef Slope	1995	1998	635	Maximum	30.5	31.7	30.3
				Date of maximum	15 Feb 1998	12 Feb 1998	15 Feb 1998
Cattle Bay	16 Jul	30 May		Mean	27.7	28.8	26.9
(Orpheus Is)	1994	1998	729	Maximum	31.5	32.6	30.9
Reef Flat				Date of maximum	3 Feb 1998	8 Feb 1998	2 Feb 1998
Pioneer Bay	17 Jul	30 Apr		Mean	27.8	28.1	27.5
(Orpheus Is)	1994	1998	729	Maximum	Maximum 30.6 31.8		30.4
Reef Slope			····	Date of maximum	19 Feb 1998	1 Feb 1998	18 & 19 Feb 1998
Geoffrey Bay	18 Dec	2 Mar		Mean	28.7	30.3	27.3
(Magnetic Is)	1992	1998	1,015	Maximum	32.3	34.7	31.7
Reef Flat		***		Date of maximum	4 Feb 1998	8 Feb 1998	5 Feb 1998
Heron Is	24 Nov	16 Jun		Mean	26.0	28.6	24.0
Reef Flat	1995	1998	493	Maximum	30.2	35.4	28.6
				Date of maximum	22 Feb 1998	23 Feb 1998	22 Feb 1998

Table 1. Summary of daily SST statistics (°C) from 8 GBRMPA data loggers for the summer (October-March) 6 months of the year.

RESULTS

Comparisons of data sets

GBRMPA data loggers and IGOSS blended satellite

The agreement between absolute weekly SSTs from GBRMPA data loggers and IGOSS varied with location (Figure 2). At Coconut Beach flat and Geoffrey Bay flat, for example, the IGOSS data appeared to consistently record lower summer maxima and higher winter minima, ie dampen the annual cycle. At Pelorus Island flat, the difference between the two data sets was greater for the winter minima than for the summer maxima. At Heron Island, in the southern GBR, the IGOSS appeared to match the summer maxima but record higher SSTs than the data loggers during the remainder of the year. At the Myrmidon Reef flat site (located offshore at the shelf edge) there appeared to be remarkable agreement between the *in situ* data logger and the blended satellite data.

The correlation coefficients between the pairs of weekly SSTs were all highly significant but will obviously be inflated by the presence of the annual cycle in both series. More informative about the level of agreement of at least the temporal variations of the two series (rather than absolute values) were the correlations between the week-to-week changes in SSTs. These were all significant at the 5% level : 0.35 (n=109) for Coconut Beach flat, 0.54 (n=231) for Pelorus Island flat, 0.61 (n=157) for Myrmidon Reef flat, 0.45 (n=269) for Geoffrey Bay flat and 0.54 (n=131) for Heron Island flat. (N.B. for comparison, the correlation between week-to-week SSTs at Pelorus Island slope and Pelorus Island flat was 0.85, n= 171).

Thus, the temporal variations in SSTs measured in the two totally independent data sets were significantly correlated, although the strength of the relationship varied with location (ie agreement was better at some sites than others).

Comparisons of monthly averages for Geoffrey Bay flat (the longest available GBRMPA logger record) with monthly IGOSS data illustrate a number of features. First, (Figure 3a and 3b) the dampened annual cycle of the IGOSS data compared with the reef flat logger. Second, at the monthly level, a significant level of agreement (r = 0.71) between the anomalies recorded by the two independent data sets. (ie the level of agreement was improved with averaging over longer time periods).

GOSTA "ships of opportunity" and IGOSS blended satellite

Comparisons between the GOSTA and IGOSS SST data averaged for the latitudinal boxes (see Figure 1) were made for the common period, January 1982 through December 1994. Annual average SSTs from the two data sets were in good agreement (Figure 4a) with differences not exceeding 0.2° C. The average annual range (between mean annual maximum and minimum SSTs) also showed a very similar spatial distribution along the northeast Australian coast (Figure 4b). Generally, the IGOSS data set showed a slightly dampened annual range (~-0.2 to -0.4° C) compared with the GOSTA data set. Both databases clearly showed a local maximum in the annual range from about 21-24°S.

Differences between the two data sets for average monthly values are illustrated for alternate latitude bands in Figure 5. Generally, the IGOSS set recorded cooler monthly mean SSTs to the south of the GBR for all months except winter. In the central and northern GBR the IGOSS data set tended to record higher SSTs in winter. A common feature at all latitudes was for the IGOSS to record cooler SSTs in November. Differences in long-term monthly means obtained from the two data sets ranged from -0.5° C to $+0.6^{\circ}$ C.



Figure 2. Weekly SSTs for 5 GBRMPA loggers and closest IGOSS 1° square and difference in SSTs (GBRMPA-IGOSS). Correlation coefficient (r) also given.



Figure 3. Comparison of monthly SSTs for Geoffrey Bay flat GBRMPA and IGOSS for a) 1993-98 monthly means, b) monthly SSTs and c) monthly SST anomalies.

Agreement between monthly anomalies from the two data sets (over the 1982-94 common period) was generally quite high (see Figure 6). The correlation between monthly anomalies ranged from 0.70 to 0.84. (NB not including IGOSS data for 22.5°S which has some sort of error). Thus, over the common period the two data sets had ~50 to 70% variance in common. The major warming and cooling events along the northeast Australian coast were evident in the two data sets though there were some differences. Differences between individual monthly anomalies from the two data sets were as much as $\pm 1.4^{\circ}$ C.

The question arises as to whether the differences between the IGOSS and GOSTA SST data sets are random. There are two reasons to suspect that they are not. First, the IGOSS "satellite" data are blended and tuned with *in situ* observations. For the period from 1982 to 1989 these *in situ* data include "ships of opportunity" observations from the Comprehensive Ocean Atmosphere Data Set (COADS; see Reynolds and Smith, 1994). COADS and GOSTA both draw upon the same "ships of opportunity" data. Thus, we would expect the agreement between the IGOSS and GOSTA data sets to be better in the period 1982-1989 compared with the later period, 1990-1994. A second potential source of differences relates to the influence of cloud cover on satellite estimates of SSTs. Cloud cover prevents a clear view of the sea surface and can, therefore, reduce confidence in the accuracy of SST estimates made from satellites. In the region examined here, this should be more of problem in the summer months (during the seasonal summer monsoon) compared with the winter



Figure 4. Annual average (a) and average annual range (b) for IGOSS and GOSTA SSTs, 1982-1994, for 1°-latitude bands (see Figure 1) from 10.5-29.5°S.

months (which are relatively cloud free) and be greater in the more northerly parts of the region (where cloud cover is also greatest).

Correlations between the GOSTA and IGOSS monthly SST anomalies were, therefore, examined separately for a) the summer 6 months of the year (October to March) and b) the winter 6 months of the year (April to September). The correlations were also examined separately for the periods 1982-1989 and 1990-1994. The results summarized by latitude band are shown in Figure 7. (NB break due to erroneous IGOSS data at 22.5°S). The effect of "tuning" with common data did appear to impact on the magnitude of the correlation coefficients. With the exception of the far north in summer and the far south in winter, the magnitude of the correlations between the two data sets was lower in the more recent period. Second, the effect of increased cloud cover in the north during summer also appeared to influence the level of agreement between the two data sets. The differences between the magnitude of the summer and winter correlations were most marked north of 22°S from 1982-1989 and south of 23°S in the later period, 1990-1994.

How unusual was the 1997-1998 summer season?

Evidence from GBRMPA SST data

The advantage of the GBRMPA SST loggers is that they record high-resolution (daily average, daily maximum and daily minimum SSTs) at reef sites, ie where the corals are living. The present disadvantage is the shortness of the records. The course of daily average SSTs for the 8 data logger sites over the two most recent summer seasons is shown in Figure 8. The 30°C temperature is also marked as this has been suggested to be a threshold for coral bleaching to occur (see, for example, Brown, 1997a) though it appears to be most likely that the threshold for bleaching varies with mean thermal conditions of the particular reef site (eg Glynn, 1996; Brown, 1997b; Jones *et al.*, 1997; Podesta and Glynn, 1997). All sites with the exception of Myrmidon reached this 30°C threshold during late January to mid-February 1998. Also remarkable, given that these sites range from Coconut Beach at ~16°S in the north to Heron Island at ~23°S in the south of the GBR, was the halt



Figure 5. Difference in monthly means (1982-94) between IGOSS and GOSTA SSTs for alternate 1°-latitude bands. Positive values (light stippling) indicate IGOSS warmer than GOSTA and negative values (dark stippling) indicate IGOSS cooler than GOSTA.



Figure 6. Monthly SST anomalies (from 1982-1994 mean) for IGOSS (bold) and GOSTA (light) data sets for alternate 1°-latitude bands. Correlation coefficient (r) between both series also given.



Figure 7. Latitudinal distribution of correlations between IGOSS and GOSTA monthly SST anomalies for a) summer 6 months and b) winter 6 months and two time periods.

in the rise of the daily SSTs in early January 1998. This short-term cooling followed the exceptional flooding event along the central Queensland coast on January 10th 1998 associated with a tropical low and may also be associated with Tropical Cyclone Katrina. Without exception, the maximum observed daily average, daily maximum and daily minimum temperatures (Table 1) at each of the 8 sites occurred in late January or February 1998.

The course of daily average, daily maximum and daily minimum SSTs for the longest, continuous record, Geoffrey Bay flat is shown in Figure 9 for the last 6 years. The 30°C temperature is again highlighted. Daily average SSTs at Geoffrey Bay usually reach 30°C each summer (Figure 9a). Similarly, daily maximum SSTs typically reach and exceed for a number of days the 30°C threshold (Figure 9b). Daily minimum SSTs have exceeded 30°C in 4 of the past 6 summer seasons. This would suggest that 30°C is not a straightforward threshold for coral bleaching to occur. The second threshold line in Figure 9 is an attempt to develop a threshold relevant to each reef site in the absence of long-term daily SSTs and experimental data. The value represents the average SSTs + 1sd for the respective daily average, daily maximum and daily minimum series for the summer 6 months of the year (October to March). This was close to 30°C for daily average temperatures, below 30°C for daily minimum SSTs and 2°C above for daily maximum SSTs.

These "thresholds' were computed for the daily average, daily maximum and daily minimum SSTs at each of the 8 logger sites. The following two parameters were then computed for each site and SST series: 1) the number of days the threshold was exceeded and b) the degree days above the threshold (ie (SST-threshold) summed over the number of days the threshold is exceeded). The results are summarized for the 8 sites and available years in Table 2 and plotted for the longest record, Geoffrey Bay flat, in Figure 10. At most sites the 1997-98 season was characterized by the greatest number of days above the respective thresholds and also the greatest number of degree days. In some cases, eg Pioneer Bay slope, the number of days exceeding the threshold was similar or even greater in 1994-95 compared with 1997-98 (see Table 2). The main difference between



Figure 8. Daily average SSTs for 8 GBRMPA loggers from 20th July 1996 through 1998. 30°C shown as dashed line.

these two years at this site was the higher number of degree days. Thus, although based on a very short number of years, the available daily SST data for reef sites along the GBR indicates that the 1997-98 summer season was unusual both in the number of days SSTs were above given thresholds and also in the intensity with which SSTs exceeded the thresholds.



Figure 9. Geoffrey Bay flat (Magnetic Island) a) daily average, b) daily maximum and c) daily minimum SSTs, 18th December 1992 to 2nd March 1998. Dashed horizontal line is 30°C and solid horizontal line is respective temperature threshold (see text).

Evidence from IGOSS SST data

The IGOSS data set provides information about SSTs for the most recent 17 austral summer seasons along the northeast Australian coast. Studies such as Podesta and Glynn (1997) have demonstrated that various measures of warm season SSTs are all inter-related. Here one of these parameters, the maximum monthly mean SST observed in each summer season, is used to assess how unusual the 1997-98 season was in the vicinity of the GBR. Maximum monthly mean SSTs for each latitude band were extracted for each summer from 1982-83 to 1997-98. Anomalies from the 17-year mean value are plotted in Figure 11 for alternate 1°-latitude bands.

The 1997-98 summer maxima were the warmest of the 17-year record for all latitude bands except 11.5-13.5°S and 16.5-17.5°S. For the latter two regions, 1997-98 ranked either the second or third most extreme maxima during the record period. The next most extreme summers were either 1981-82 or 1986-87. Averaged over the GBR region (10.5-24.5°S; SSTs tend to vary in a similar manner along the length of the GBR; see Lough, 1994, 1998), 1997-98 was the most extreme year with a

Table 2. Number of days and number of degree days (in brackets) daily average, daily maximum and daily minimum SSTs exceed summer season"threshold" for 8 GBMRPA data loggers. – indicates no data and * indicates incomplete season.

	Threshold °C	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98
			D	aily Average			
Coconut Beach Reef Flat	29.6	-	-	-	-	13 (4)	35 (40)
Myrmidon Reef Flat	28.9	-	-	-	19 (6)	0 (0)	39 (20)
Pelorous Island Reef Flat	29.3	-	31 (9)*	15 (4)	22 (6)	6(1)	35 (38)
Pelorous Island Reef Slope	29.2	-	-	-	23 (3)	0 (0)	33 (25)
Cattle Bay (Orpheus Is) Reef Flat	29.2	-	-	28 (11)	28 (6)	7 (2)	37 (43)
Pioneer Bay (Orpheus Is) Reef Slope	29.2	-	-	36 (13)	33 (8)	5 (<1)	32 (30)
Geoffrey Bay (Magnetic Is) Reef Flat	30.2	17 (5)*	26 (22)	20 (12)	15 (3)	7 (<1)	54 (49)*
Heron Is Reef Flat	27.7	-	-	-	22 (12)*	11(4)	47 (42)
			Da	aily Minimum	l		
Coconut Beach Reef Flat	29.1	-	-	-	-	15 (4)	32 (39)
Myrmidon Reef Flat	28.5	-	-	-	22 (8)	2 (<1)	38 (19)
Pelorous Island Reef Flat	28.5	-	35 (12)*	14 (5)	22 (8)	9 (3)	38 (37)
Pelorous Island Reef Slope	28.8	-	-	-	24 (5)	1 (<1)	17 (17)
Cattle Bay (Orpheus Is) Reef Flat	28.5	-	-	20 (8)	26 (5)	9 (3)	43 (44)
Pioneer Bay (Orpheus Is) Reef Slope	29.0	-	-	52 (15)	30 (8)	5 (<1)	29 (21)
Geoffrey Bay (Magnetic Is) Reef Flat	29.0	24 (12)*	30 (23)	20 (12)	10 (3)	11 (3)	48 (53)*
Heron Is Reef Flat	25.9	-	-	-	12 (7)*	15 (6)	49 (46)
			Da	aily Maximun	1		
Coconut Beach Reef Flat	30.4	-	-	-	-	18 (4)	39 (42)
Myrmidon Reef Flat	29.4	-	-	-	23 (8)	2 (<1)	44 (25)
Pelorous Island Reef Flat	30.3	-	33 (13)*	16 (4)	26 (11)	4(1)	39 (44)
Pelorous Island Reef Slope	29.5	-	-	-	12 (4)	2 (<1)	32 (35)
Cattle Bay (Orpheus Is) Reef Flat	30.3	-	-	35 (23)	13 (8)	9 (2)	42 (45)
Pioneer Bay (Orpheus Is) Reef Slope	29.6	-	-	32 (12)	25 (9)	3 (1)	34 (37)
Geoffrey Bay (Magnetic Is) Reef Flat	32.0	14 (9)*	46 (31)	28 (20)	21 (12)	7 (3)	43 (46)*
Heron Is Reef Flat	30.9	-	-	-	28 (29)*	14 (13)	39 (62)



Figure 10. Number of days and number of degree days above "threshold" for Geoffrey Bay Flat (Magnetic Is) for a) daily average, b) daily maximum and c) daily minimum SSTs. Note, 1992-93 and 1997-98 are incomplete seasons with only 104 and 153 days of a possible 182 days, respectively.

maximum monthly mean SST anomaly of $+0.72^{\circ}$ C, followed by $+0.53^{\circ}$ C in 1986-87 and $+0.45^{\circ}$ C in 1981-82. Thus, the evidence from the IGOSS data set indicates that the 1997-98 summer season had the warmest SST maxima on the GBR over the period 1982 to 1998.

The information obtained from the IGOSS and GOSTA data sets on SST maxima variations was not, however, in total agreement. Anomalies for the region of the GBR ($10.5-24.5^{\circ}$ S) with respect to the common period 1982-1994 (Figure 12) showed some conflicts between the two data sets, eg 1981-82 was comparable to 1986-87 in the IGOSS data set but close to average for the GOSTA data set. The correlation between these two average series was 0.79. When examined by latitude band (not shown) the largest disagreements between the two data sets occurred between 10-15.5°S with ~35-40% variance in common. Agreement was better from 16.5-26.5°S with ~50-80% variance in common.

The historical perspective from the GOSTA data set, 1903-1994.

Average conditions

Average monthly SSTs for alternate 1°-latitude bands along the northeast Australian coast are shown in Figure 13. Maximum monthly mean SSTs usually occur in January-February with minimum monthly mean SSTs in July-August. The mean annual cycle varies from a rather broad



Figure 11. Maximum monthly mean SST anomalies, 1982-98, from IGOSS data set for alternate 1° -latitude bands. Mean maxima also given.

peak in summer in the north (with maxima occurring for example from December-February) to a sharper peak in the south with the maxima generally occurring in February. The average annual



Figure 12. Comparison of GOSTA and IGOSS maximum monthly mean SST anomalies from 1982-1994 mean for 10.5-24.5°S.

range based on the 1903-1994 "climatology" was typically 4-6°C (see Figure 4b). At any given latitude the difference between the observed maximum monthly mean SST and observed minimum monthly mean SST over the period 1903-1994 was about 3°C larger, ie from 6-9°C (Figure 14). This might, therefore, be a more representative "window" of the SST range within which coral reef ecosystems of the GBR operate than the average annual range (cf Figure 4b).

Variations associated with ENSO and anti-ENSO events

Monthly SST anomalies (from the respective 1903-1994 monthly means) were calculated for each latitude band. These were then averaged from January to December of the following year (24 months) for 23 ENSO events and 23 anti-ENSO events (eg for the 1982-83 ENSO event, average anomalies covered January 1982 through December 1983). This "compositing" technique emphasizes SST anomalies common amongst the different ENSO (and anti-ENSO) events and de-emphasizes those SST anomalies that are not common. The average monthly SST anomalies were then tested for significant difference from the long-term mean (Mitchell *et al.*, 1966). The resulting patterns are shown for alternate latitude bands for ENSO events (Figure 15) and anti-ENSO events (Figure 16).

There are two components to the "average" SST anomaly signal associated with ENSO events along the northeast Australian coast (see also Lough, 1994). These are cooler than normal SSTs in the prior winter that extend to about the southern tip of the GBR and warmer than normal SSTs in the summer season that extend from 10.5-29.5°S. In the far north (eg Figure 15a and 15b) this anomalous warming extends across the normal seasonal SST maximum. Further south (eg Figure 15d and 15e) the anomalous warming occurs after the normal SST seasonal maximum ie late summer.

Although there was a tendency for anti-ENSO events to be associated with opposite sign anomalies to ENSO events on the northeast Australian coast, the magnitude, extent and significance of the SST anomalies were much less (Figure 16). Thus, significant warming in the prior late winter-early summer season was largely confined to the northern GBR (Figure 16a, 16b and 16c). Significant cooling in the summer season was not widespread or significant.

Figure 17 summarizes the "average" ENSO and anti-ENSO signals over the GBR region (10.5-24.5°S).



Figure 13. Monthly mean SSTs, 1903-1994 (± 1sd shown as error bars), from GOSTA data set for alternate 1°-latitude bands. Mean annual SST also given. Note different temperature scales.



Figure 14. Observed maximum and minimum monthly mean SSTs, 1903-1994 for each 1°-latitude band from GOSTA data set.

Was 1997-98 a "typical" ENSO for the GBR?

No two ENSO events are alike (eg Allan *et al.*, 1996). Each evolves in a slightly different manner. There are, however, features (cf Figures 15 and 17a) that appear characteristic of such events in the vicinity of the GBR. Here I examine whether the 1997-98 was a typical event for the GBR region.

Observed SST anomalies (from IGOSS) for four recent ENSO events are compared with the average ENSO "signal" for the GBR region (10.5-24.5°S) in Figure 18. The 1982-83 event clearly followed the average signal with prior winter cooling and summer warming (Figure 18a). The overall correlation between the "average" signal and observed SST anomalies for the 24 months was 0.59. The magnitude of the correlation varied spatially (not shown), being greatest (>50% variance in common) north of 16.5°S. The 1986-87 event was not typical, with no evidence of prior winter cooling and only a slight warming evident in early summer (Figure 18b). The overall correlation was -0.19. The 1991-92 event was also atypical with prior cooling only evident in very early winter and no marked warming in summer (Figure 18c). The 1997-98 event did, however, show strong similarities with the "average" ENSO signal (Figure 18d) with an overall correlation (over 18 months) of 0.79. Prior winter cooling was weakly evident followed by marked summer warming. Spatially, greatest agreement between the average signal and the observed SST anomalies occurred south of 18.5°S (>50% variance in common). Thus, the 1997-98 ENSO event was associated with a reasonably "typical" SST anomaly signal along the northeast Australian coast.

In contrast to the SST anomalies along the northeast Australian coast, summer rainfall variations in Queensland did not follow the typical ENSO signal in 1997-1998. Northeast Australia is one of the regions around the world considered to experience consistent patterns of rainfall anomalies in association with ENSO and anti-ENSO events (eg Ropelewski and Halpert, 1996). ENSO events are usually associated with a weakened summer monsoon and drier than normal conditions with a strengthened monsoon and wetter than normal conditions in anti-ENSO years (Lough, 1994). Rainfall in the 1997-1998 summer season was close to average for Queensland as a whole and well above average for certain regions (see Climate Monitoring Bulletin, Australia, Issue No. 143 and 146, Australian Bureau of Meteorology).

Are summer seasons becoming more extreme?

Superimposed on decadal variability (illustrated by the 10-year Gaussian filter) maximum monthly mean SST anomalies significantly warmed over the 91-year record period, 1904-1994, at all latitudes from 13.5 to $29.5^{\circ}S^{1}$ (Figure 19). Warming was greatest to the south of the GBR (Figures

¹ NB No allowance has been made for the presence of autocorrelation in assessing the significance of linear trends. This may cause the level of significance to be overestimated.



Figure 15. Average monthly SST anomalies (bars, scale on left-hand axis) associated with 23 ENSO events and mean annual cycle (line, scale on right-hand axis), for alternate 1°-latitude bands from GOSTA data set. Anomalies in bold are significantly different from the long-term mean at the 5% level.



Figure 16. Average monthly SST anomalies (bars, scale on left-hand axis) associated with 23 anti-ENSO events and mean annual cycle (line, scale on right-hand axis), for alternate 1°-latitude bands from GOSTA data set. Anomalies in bold are significantly different from the long-term mean at the 5% level.



Figure 17. Average monthly SST anomalies (bars, scale on left-hand axis) for GBR (10.5-24.5°S) associated with a) 23 ENSO and b) 23 anti-ENSO events, from GOSTA data set. Mean annual cycle also shown (line, scale on right-hand axis). Anomalies in bold are significantly different from the long-term mean at the 5% level.

19h, 19i, and 19j) where the linear trend accounted for \geq 30% of the variance. There has been no significant warming of summer season SST maxima in the far north of the GBR (Figure 19a).

This increase in summer season extremes was also demonstrated by the frequency of years in 3 subperiods in which the maxima was ≥ 1 sd above the long-term mean (Table 3). In the first 30 years of the record such extremes occurred in 10% or less years along the GBR (10.5-24.5°S), ie about once every 10 years. In the most recent 31-year period, 1964-1994, such extremes occurred about once every four years. The greater warming trend to the south of the GBR was also evident with such extremes occurring about every two years in the most recent period compared with only about once every 30 years in the earlier part of this century.

The ten years of most extreme monthly mean SST maxima (from 1904 to 1994) for each latitude band are listed in Table 4. SST anomalies in 1987 were the most extreme of the 91-year record period throughout most of the region. For the GBR ($10.5-24.5^{\circ}$ S) the years in which at least 10 of the 15 boxes had SST maxima \geq 1sd above the mean were: 1910, 1924, 1935, 1946, 1958, 1963, 1964, 1970, 1972, 1977, 1980, 1986 and 1987. 1980 and 1987 were both years of documented coral bleaching on the GBR (Berkelmans and Oliver, in press). Although 1982 was also a documented bleaching year (*ibid*), it does not appear to be unusually warm in the GOSTA data set but was unusually warm in the IGOSS data set (see Figure 12). The reasons for this difference between the two data sets need to be examined further.

Thus, evidence from the GOSTA data set for the period from 1904-1994 suggests that summer season SST extremes are becoming more frequent over most of the GBR but especially to the south. Given that 1987 was the most extreme summer on the GBR within the period 1904 to 1994, and 1987 was the second most extreme year after 1998 in IGOSS over the period 1982-1998, 1998 was likely to have been the most extreme year during the past 95 years.



Figure 18. Average monthly SST anomalies (bars, left hand axis) for GBR (10.5-24.5°S) associated with 23 ENSO events and observed monthly SST anomalies (line, right-hand axis) for a) 1982-1983, b) 1986-87, c) 1991-92 and d) 1997-98 ENSO events. Correlation coefficient (r) between both series also given.

Is the SST climate of the GBR changing?

Evidence presented in the preceding section related only to SST maxima during the summer warm season. Here, I examine whether these changes are part of an overall change in the SST climate of of the GBR. Annual average (January to December) SSTs significantly increased at all latitudes along the northeast Australian coast from 1903 to 1994 (Figure 20). The warming appears to have occurred mainly since the late 1950s at all latitudes. The magnitude of the warming trend was least in the far north of the GBR (eg Figure 20a and 20b) where it accounted for less than 20% of the variance and was greatest to the south of the GBR (Figure 20h, 20i and 20j) where it accounted for more than 40% of the variance.



Figure 19. Maximum monthly mean SST anomalies, 1904-1994, for alternate 1°-latitude bands. Thick line is 10-year Gaussian filter. Dashed line (where drawn) is significant linear trend and variance explained by linear trend (R²) value also given.

Region	1904-1933	1934-1963	1964-1994
10.5°S	10	6	4
11.5°S	10	8	3
12.5°S	10	6	4
13.5°S	14	6	4
14.5°S	10	6	4
15.5°S	14	4	4
16.5°S	14	5	3
17.5°S	14	5	4
18.5°S	10	6	4
19.5°S	14	6	4
20.5°S	10	6	4
21.5°S	10	6	4
22.5°S	10	6	4
23.5°S	10	8	3
24.5°S	30	8	2
25.5°S	30	8	2
26.5°S	30	8	2
27.5°S	30	10	2
28.5°S	14	10	2
29.5°S	30	10	2

Table 3. Return periods (in years) for maximum monthly mean SST \geq 1sd of 1904-1994 mean for 1°-latitude bands and three sub-periods.

Table 4. Average maximum monthly mean SST (GOSTA, 1904-1994) and 10 warmest years for 1°-latitude bands.

Region	Mean					R	ank				
	°C	1	2	3	4	5	6	7	8	9	10
10.5°S	29.2	1990	1940	1929	1970	1944	1983	1987	1973	1913	1941
11.5°S	29.3	1940	1929	1983	1 987	1970	1 94 4	1990	1973	1913	1946
12.5°S	29.2	1987	1983	1 940	1 970	1929	1986	1973	1980	1 97 1	1946
13.5°S	29.1	1987	1983	1940	1 970	1986	1929	1980	1973	1971	1958
14.5°S	28.9	1987	1983	1970	1 986	1940	1973	1958	1964	1 97 1	1980
15.5°S	28.9	1987	1970	1983	1910	1986	1973	1958	1964	1935	1940
16.5°S	28.8	1987	1910	1970	1958	1973	1935	1964	1986	1 97 1	1963
17.5°S	28.8	1987	1910	1935	1958	1970	1 96 4	1973	1986	1929	1938
18.5°S	28.5	1987	1910	1935	1958	1970	1964	1973	1938	1 977	1986
19.5°S	28.2	1987	1910	1935	1958	1970	1973	1964	1994	1 986	1977
20.5°S	27.9	1935	1910	1987	1970	1958	1986	1938	1973	1 9 77	1 97 1
21.5°S	27.8	1935	1910	1987	1 938	1 970	1986	1958	1973	1 97 7	1980
22.5°S	27.5	1935	1910	1987	1938	1986	1970	1980	1958	1977	1973
23.5°S	27.2	1935	1910	1938	1 987	1980	1 986	1970	1958	1982	1973
24.5°S	26.8	1987	1982	1980	1 938	1986	1935	1970	1958	1973	1985
25.5°S	26.4	1987	1982	1980	1958	1986	1970	1985	1973	1938	1992
26.5°S	26.2	1987	1980	1982	1958	1973	1970	1943	1992	1985	1938
27.5°S	26.0	1987	1982	1980	1973	1958	1970	1943	1990	1992	1938
28.5°S	25.7	1987	1982	1973	1980	1958	1970	1943	1981	1971	1990
29.5°S	25.5	1987	1973	1982	1958	1970	1980	1919	1981	1943	1971



Figure 20. Annual average SST anomalies, 1903-1994, for alternate 1°-latitude bands. Thick line is 10-year Gaussian filter. Dashed line (where drawn) is significant linear trend and variance explained by linear trend (R²) value also given.

The warming trend evident in annual and maximum SSTs was also evident at other times of year (Figure 21). Warming was, however, greatest (up to 0.1°C per decade) along much of the GBR in the late summer months (JFM, Figure 21a) and was weakest in early winter months (AMJ, Figure 21b).

Thus, there appears to be good evidence that SSTs along the GBR have warmed over much of the present century especially in the summer season. Warming has been greatest in magnitude south of the GBR.

Evidence from other climatic indices

Annual anomalies of SSTs for the GBR region (10.5-24.5°S) and south of the GBR (25.5-29.5°S) were compared with temperature and rainfall variations in Queensland (Lough, 1997), combined land and sea temperatures for the Southern Hemisphere (Houghton et al., 1996) and the Tahiti-Darwin index of the Southern Oscillation (SOI). Significant warming trends were evident in Queensland average and minimum (nighttime) temperatures and the Southern Hemisphere temperature index. (Trends in Queensland temperatures in recent decades appear to be the largest in comparison with other parts of Australia eg www.bom.gov.au/bmrc/mrlr/daj/tempanal.htm). There were no significant trends in the SOI or Queensland rainfall. Annual SST variations on the GBR and to the south were significantly correlated with all three Queensland temperature indices, though the magnitude of the correlations was greatest for minimum and average rather than maximum temperatures (Table 5). The correlations were also significant for the original and residual (after removal of decadal variability) data. Thus, SST variations along the northeast Australian coast were similar to those of the adjacent land area (Figure 22). Weak, but significant, correlations also occurred with Queensland annual rainfall and the SOI for SST variations of the GBR region (10.5-24.5°S) but not for SSTs to the south of the GBR. Annual SST variations, especially those to the south of the GBR, all appear to track those of the Southern Hemisphere land and marine temperatures. This suggests that the increase in SSTs over the present century may be part of, at least, a hemispheric phenomenon.

Table 5. Correlation between annual SST variations on the northeast Australian coast (GBR and region to south of GBR) and other regional climatic indices. Correlation coefficients in brackets are for the residual series from the 10-year Gaussian filter (see Figure 22). Period is 1903-1994 except for Queensland temperature indices, 1910-1994. Values in bold are significant at 5% level.

Climatic index	SST 10.5-24.5°S	SST 25.5-29.5°S
Queensland average temperature	0.47 (0.47)	0.58 (0.57)
Queensland maximum temperature	0.28 (0.26)	0.37 (0.41)
Queensland minimum temperature	0.52 (0.53)	0.63 (0.57)
Queensland rainfall	0.27 (0.27)	0.06 (-0.01)
SH land & marine temperature	0.50 (0.16)	0.74 (0.41)
Southern Oscillation Index	0.21 (0.31)	-0.14 (-0.02)

CONCLUSIONS

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The ideal SST data set to assess the nature and significance of linkages between SST characteristics and variations of coral reef phenomena, such as coral bleaching, would have the following characteristics:

- At least daily temporal resolution to allow assessment of both the duration and intensity of SST extremes above and below particular thresholds.
- Be spatially extensive.



Figure 21. Linear trend (°C increase from 1903-1994, bar, scale on left-hand axis) and percent variance explained (line, scale on right-hand axis) for seasonal and annual SSTs. Trends are not significant at 5% level for unfilled bars.



Figure 22. Annual anomalies of a) SSTs 10.5-24.5°S, b) SSTs 25.5-29.5°S, c) Queensland average temperatures, d) Queensland maximum temperatures, e) Queensland minimum temperatures, f) Southern Hemisphere land & marine temperatures, g) Southern Oscillation Index, and h) Queensland rainfall index. Thick line is 10-year Gaussian filter. Dashed line (where drawn) is significant linear trend and variance explained (R²) also given.

- Provide measurements at various depths and locations on coral reefs. This would provide information about the absolute temperatures experienced by corals – which will vary in intensity depending on local reef conditions (eg tides, extent of flushing of lagoon water, vertical temperature stratification etc).
- Be available in near real time so that "critical" conditions can be quickly identified.
- Be of long duration (at least 30 years is needed to determine "climatological' conditions and variability about the average) so that the extent to which particular SSTs (eg January-February 1998) are unusual can be assessed.

Such an ideal data set is not, as yet, available. Elements of each of these ideal characteristics are, however, found in the three data sets used in this report. There was a significant (possibly surprising) level of agreement between the different data sets; ie they seem to be telling parts of the same story. Despite their respective weaknesses it was possible, using these data, to answer with reasonable confidence the three questions posed at the start of this report:

- 1. SST anomalies of the 1997-1998 summer season may well have been the most extreme in the past 95 years.
- ENSO events are typically associated with prior winter cooling and summer warming of SSTs on the GBR. Generally opposite, though less marked, SST anomalies are associated with anti-ENSO events². SST anomalies on the GBR during the 1997-1998 ENSO event were at least qualitatively similar to the "typical" ENSO pattern for the region.
- 3. SSTs off the northeast Australian coast have significantly warmed from 1903 to 1994. This is evident in annual and seasonal averages and summer season extremes. The frequency of extreme summer season maximum monthly SST anomalies is substantially greater in the most recent 30 years compared with the first 30 years of this century. The warming trend is greatest to the south of the GBR and also matches changes over the same time period in average and minimum temperatures over Queensland and the Southern Hemisphere land and ocean temperatures.

The rise in SSTs of the GBR over the present century has increased the frequency of warm temperature extremes during the summer season and thus, potentially, the risk of coral bleaching events. Average SSTs in the vicinity of coral reefs are projected to rise 2-3°C above pre-industrial values by the end of the 21st century (eg Houghton *et al.*, 1996; Pittock, in press). If the observed SST rise on the GBR is a response to the enhanced greenhouse effect then the frequency of warm temperature extremes is likely to continue to increase. Such an increase could result in an increasing risk of coral bleaching events and a reduction in the time for coral reefs to recover from bleaching events. In the absence of adaptive changes by coral communities this is also likely to increase reefs' vulnerability to other natural and unnatural stresses (eg Wilkinson and Buddemeier, 1994).

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 $^{^{2}}$ Current indications are that 1998-1999 will be an anti-ENSO event. It is, therefore, unlikely that SSTs on the GBR during the 1998-1999 summer season will be unusually warm (see Figure 17b).

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