Water Temperatures on the Palauan Reef Tract
Year 2000

by

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Coral Reef Research Foundation
Koror, Palau 96940

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This report offers preliminary qualitative interpretations of data collected during 2000. It is not intended to be a robust nor final treatment of the subject. Please contact the author for permission, corrections, and caveats before citing this work.

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I. Introduction:

This is the first in a series of yearly reports documenting the water temperature conditions occurring on the reefs of Palau, both in the shallow waters of the lagoon and the outer reef slope waters to about 90 m (300 feet) depth. This program began in mid-1999 and there is no separate report for 1999. The initial data from that period are included in this report. This monitoring program was started as a result of the coral bleaching event of 1998 and the realization that we did not have accurate, long-term data on water temperatures in Palau. Hopefully, this will no longer be the case.

II. Methods and Materials:

Types of Instruments

The study used Onset Hobo Pro 8 thermographs. These were chosen because of their highly precise nature (0.01^{o}C resolution) and external thermistor probe. Because they are not normally intended for underwater use, they are put inside a PVC/Plexiglas pressure-proof housing. The external thermistor probe is positioned against a metal "window" in the housing and thermally connected with silicone grease to rapidly conduct temperature changes from outside to the thermistor. The thermograph also contains an internal thermistor (inside the white plastic housing of the instrument) used for recording temperatures on a separate channel. In the event the external thermistor fails, the internal thermistor data can be used as a backup data set for temperature. However, the internal thermistor is not calibrated and its data, combined with the lag time in responding to temperature changes, must be considered less accurate than the external thermistor.

Instruments are normally set on a sample interval of 30 minutes, which allows 340 days of recording before the memory of the thermograph is full (16,320 measurements). The thermograph housing are placed on the reef at selected depths by divers. Generally, they are put in areas where a casual diver would not easily see them. They are weighted and/or attached using tie wraps.

Instruments are calibrated before and after each deployment. This is done by immersing the external probe in water (usually at the same time as several other instruments) attached by a rubber band to the bulb of a highly accurate mercury thermometer (0.01^{o}C accuracy, NIST traceable) and over a period of a few hours, the temperatures measured by the thermometer are recorded with time. At the end of the calibration run, the thermograph(s) are downloaded and their measured temperatures are compared with those from the thermometer. If there are consistent differences (high or low) between thermometer and thermograph measurements the mean of these differences is considered to be the error of thermographs and is applied as a correction factor to thermograph measurements. With these corrections, thermograph data are believed accurate within 0.1^{o}C.

Number of stations and instruments

A map of the monitoring stations is included as Figure 1. Latitude/longitude data are included in Appendix 1. During the Year 2000 the number of stations was increased from the initial 6 to 8 and the total number of instruments from 8 to 15. It was decided early in the project that it would be useful include a vertical monitoring of temperature conditions, at the Short Drop Off (SDO) station. A vertical array of three thermographs was established

(15, 55 and 90 m) there. During the year the number of instruments was increased to six, with final depths of 2, 15, 35, 55, 75 and 90 m. Additionally a second vertical station was established on the western barrier reef ("Ulong Rock") at 12 and 55 m. Finally a third vertical station was started in the west channel of Babeldaob (Toachel Mlengui), again with units at 15 and 55 m. Fifty five meters was selected as the depth for these intermediate thermographs as this is below the depth where the first slight thermoclines normally occur and previous measurements at SDO indicated there might be significant thermal variation at this depth. The establishment of units at similar depths in multiple areas around Palau will allow comparison of thermocline behavior around the archipelago.

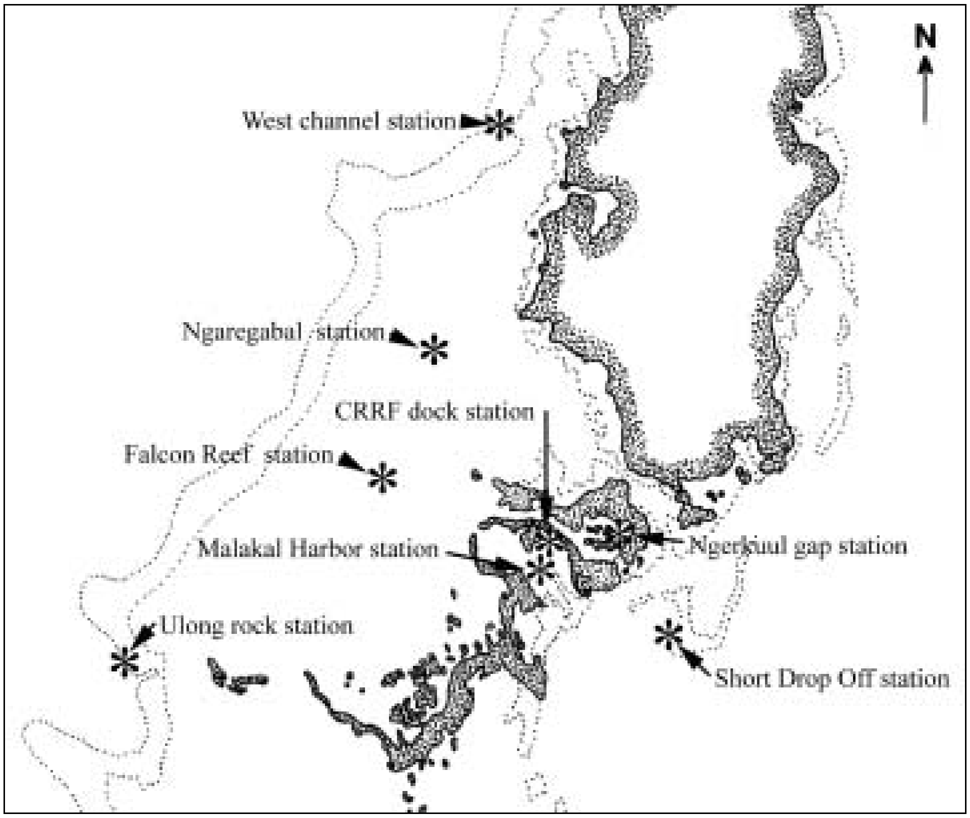

Figure 1. Location of water temperature monitoring stations on the Palauan reef tract.

Data Recovery, Management and Archiving

Data are downloaded and placed into an excel spreadsheet with the original dates and times. These data are retained intact, while they are also placed into a spreadsheet file that calculates daily and weekly means. The data are then plotted using Sigmaplot and those graphs are included in this report. Data are available in either form (raw or yearly) for others with an interest. Data are archived with CRRF and a duplicate copy lodged with the Palau International Coral Reef Center's Global Coral Reef Monitoring Network Micronesian node office.

III. Results and Discussion

Year Summary

The generalized picture of water temperatures over the year is presented in Figure 2. Weekly means at four stations; two in the lagoon (Malakal Harbor and Ngerkuul Gap) stations, one on the east (Short Drop Off) and one on the west (Ulong Rock) outer reef. Other stations have the similar profiles, but are not included to prevent having too many overlapping curves on the figure.

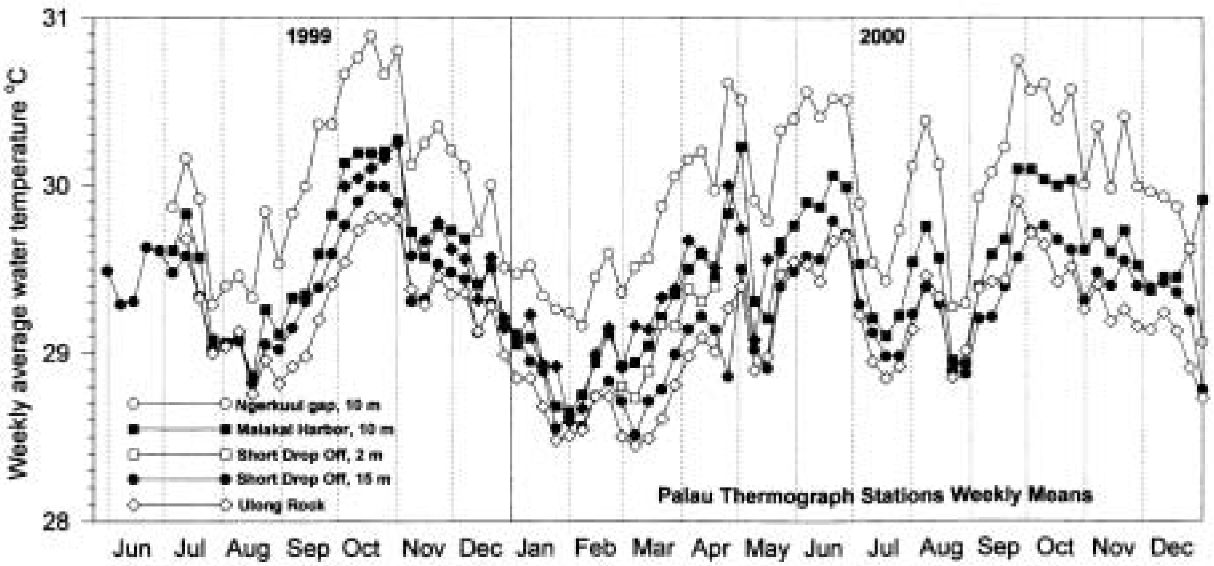

Figure 2. Weekly mean surface water temperatures at selected stations on the Palau reef tract from June 1999 through December 2000.

Lagoon temperatures were consistently higher than outer reef stations by as much as 1°C. At times during the summer of 1999 and spring to fall 2000, water temperatures exceeded the roughly 30°C threshold for coral bleaching (Brown, 1997). During spring and summer 2000 there were three distinct periods (May, July and late August) where overall water temperatures above about 30 m depth dropped as much as 1°C over the period of 1-2 weeks. Their occurrence has been correlated with weather conditions and is discussed in more detail later.

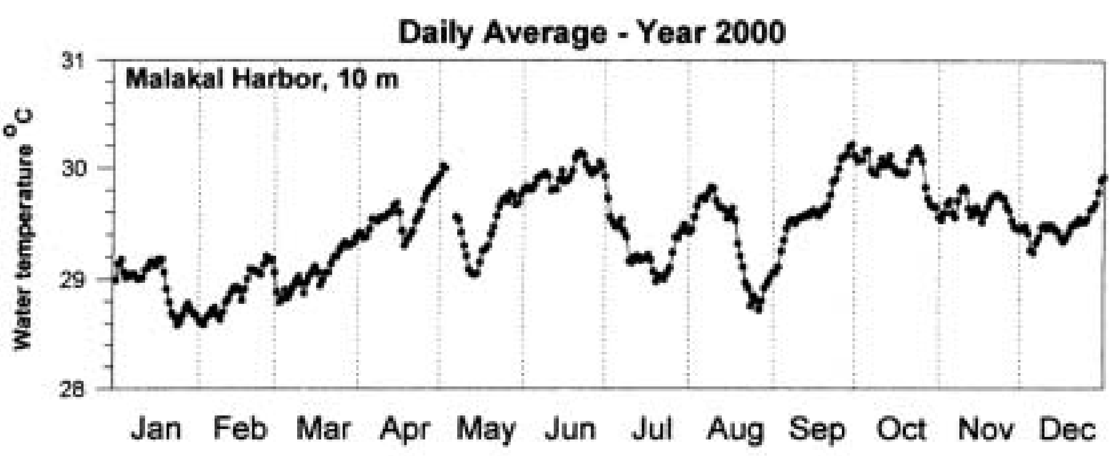

Figure 3. Mean daily water temperatures for Malakal Harbor, Koror, Palau during 2000. Gaps in data indicate the instruments were being serviced.

Figure 3 shows the daily mean water temperature profile for Malakal Harbor at 10-m depth on a reef slope. This area is a fairly typical lagoon reef area well flushed by the tides. Mean temperatures change only slightly day to day (generally no more than about 0.1°C, and typically much less), but overall trends can persist for a few weeks, resulting the significant changes seen in the weekly mean graph (Figure 2).

The Malakal station is impacted by water moving through the harbor from the large western lagoon of Palau on the falling tide and by water coming from the east through to Ngel and Lighthouse Channels on the rising tide. The tidal signal at this station is clear if data are examined on an hourly basis. Figure 4 shows a typical period in March 2000 with the temperature range during each day obviously correlated with the tide. Interestingly, not all low tides produce a similar decrease in water temperatures at this station. On the days shown, the morning high tide (semi-diurnal tides in Palau) is associated with the largest drop in water temperatures, about 0.5°C, while the afternoon high tide, which has higher tidal amplitude, shows a much smaller drop. This relationship may differ in different months, but the data here do show the changes in temperature at lagoon stations associated with the tide stage.

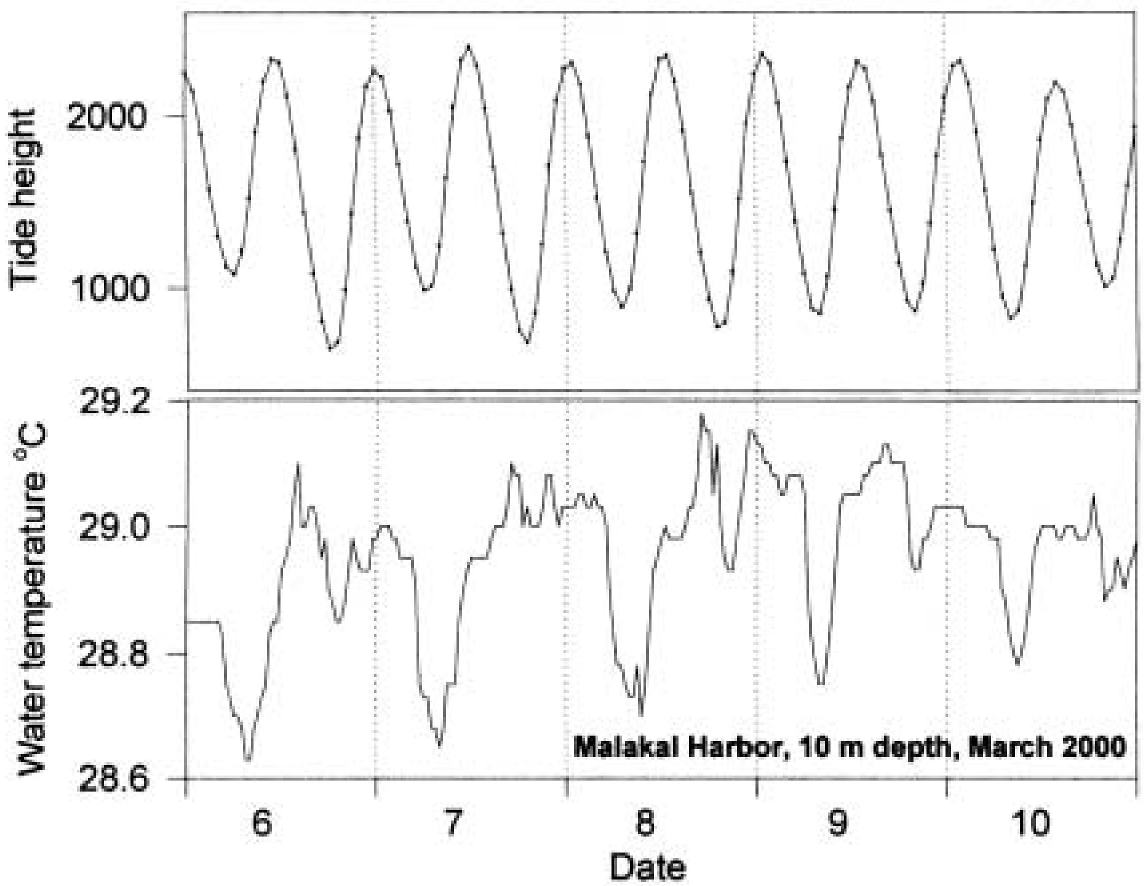

Figure 4. Relationship between tidal stage and water temperature at the Malakal Harbor station during a five-day period, March 2000.

In areas of the lagoon more strongly influenced by shallow reef flats and other areas subject to greater temperature fluctuations, the change in temperatures with the tide can be more extreme. Figure 5 shows water temperatures during two months in 1999 taken at 5 minutes intervals 2 m deep (high tide) at the CRRF dock, located only about 2 km from the Malakal station. Temperatures can vary as much as 2°C during the tidal cycle, and it would be difficult to generalize about water temperatures in such an area if measured at only one time of day. These data indicate that long-term regular sampling is the only way to get an accurate picture of the temperature regime in lagoonal areas of Palau.

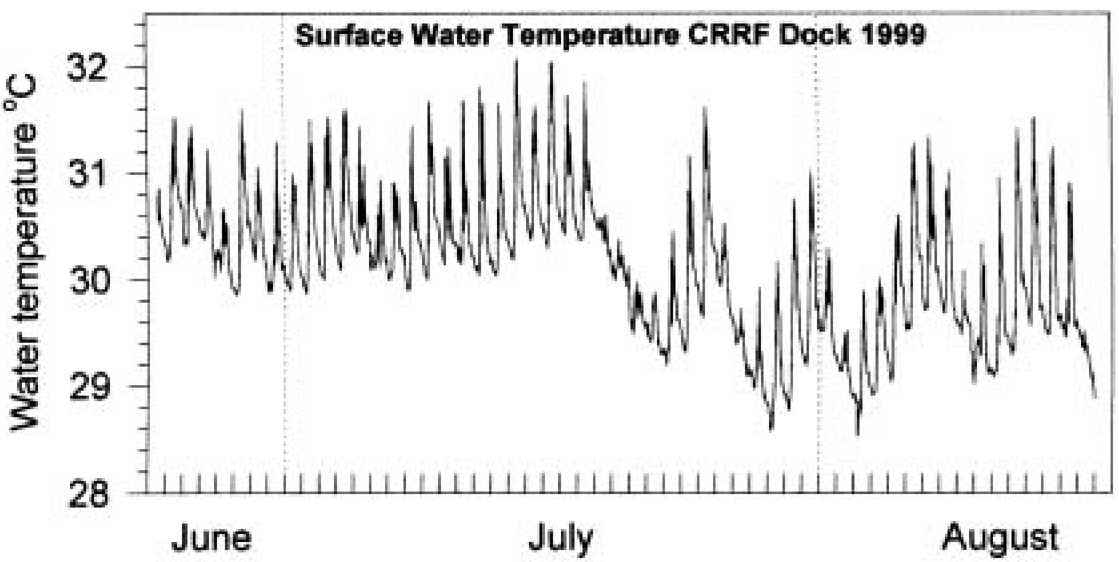

Figure 5. Water temperature at the CRRF dock during a 2-month period, summer 1999.

The daily variation in water temperatures is also related to the tidal amplitude. Figure 6 shows the hourly variation in water temperature at the Malakal Harbor station for March 2000 compared with the tidal

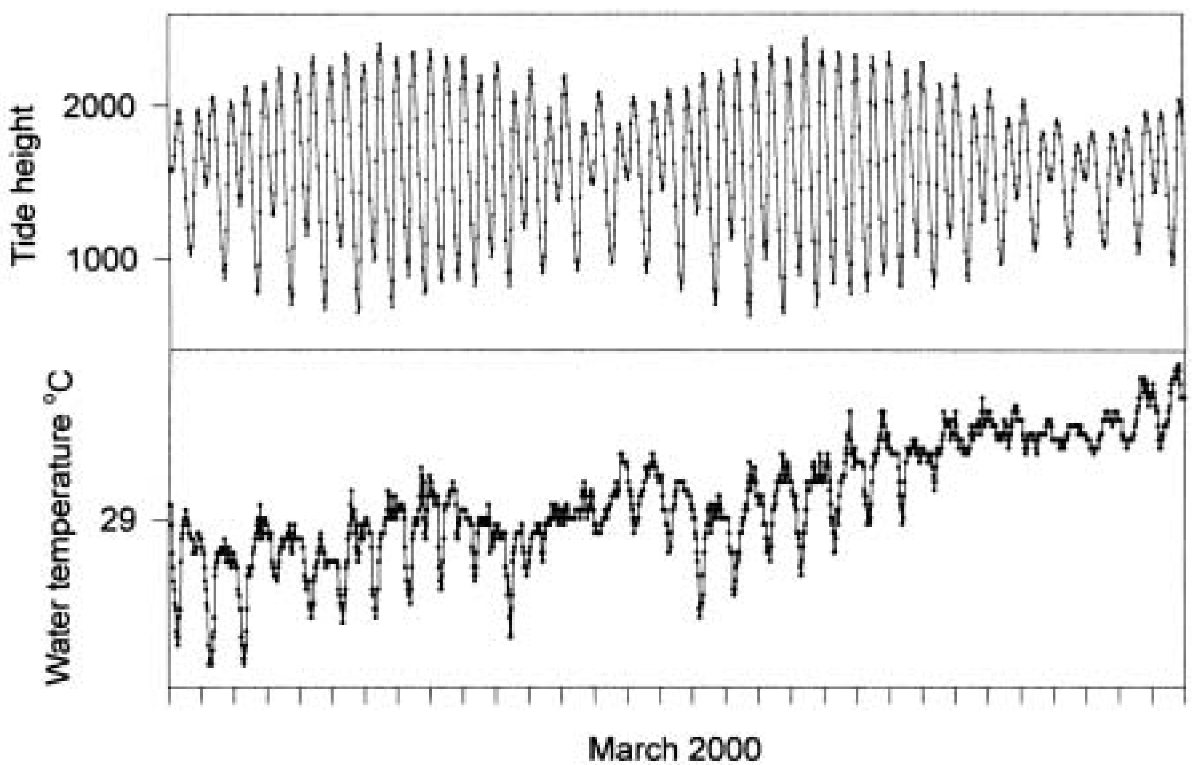

Figure 6. Comparison of daily variation in temperature with spring and neap tides, Malakal Harbor, Palau.

amplitude. There is a greater range of daily water temperature on spring tides, compared to days with neap tides. This result is not surprising since the amount of flushing and hence, transport of water of potentially different temperatures is increased during spring tides.

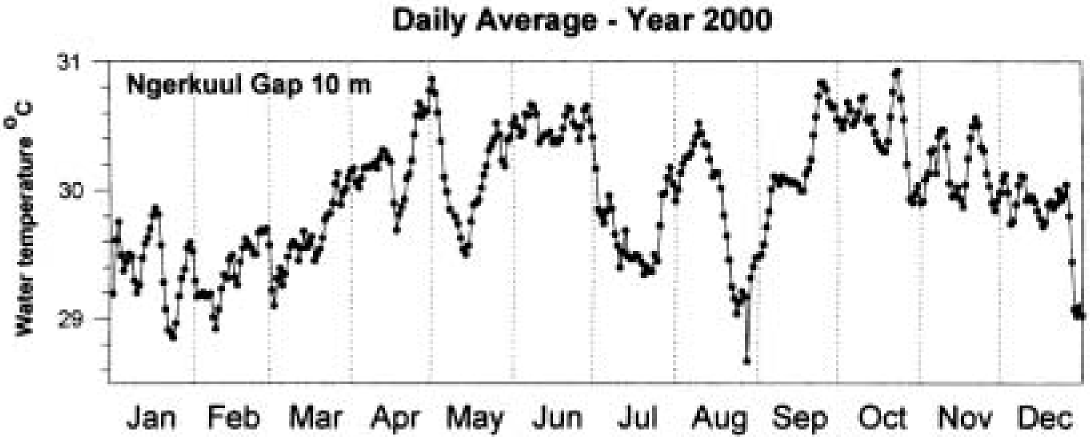

Figure 7. Daily average water temperature at the Ngerkuul gap station.

Other lagoon areas with monitoring stations have similar temperature plots to that of Malakal Harbor (Figure 2). Figure 6 shows the annual cycle for Ngerkuul Gap, one of the two drainage points for the Nikko (Iwayama) Bay in the Rock Islands near Koror. This site has the highest water temperatures of any Palau monitoring station, at times about 0.5°C warmer than other areas. Figure 8 shows the yearly cycle for Ngaregabal Reef, a central lagoon reef more isolated from the open ocean than Malakal Harbor. The cycle here shows the same general pattern, but the overall ranges are more extreme (compare to Figure 2), perhaps implying that this reef is more isolated from the overall moderating influence of the open ocean surrounding Palau.

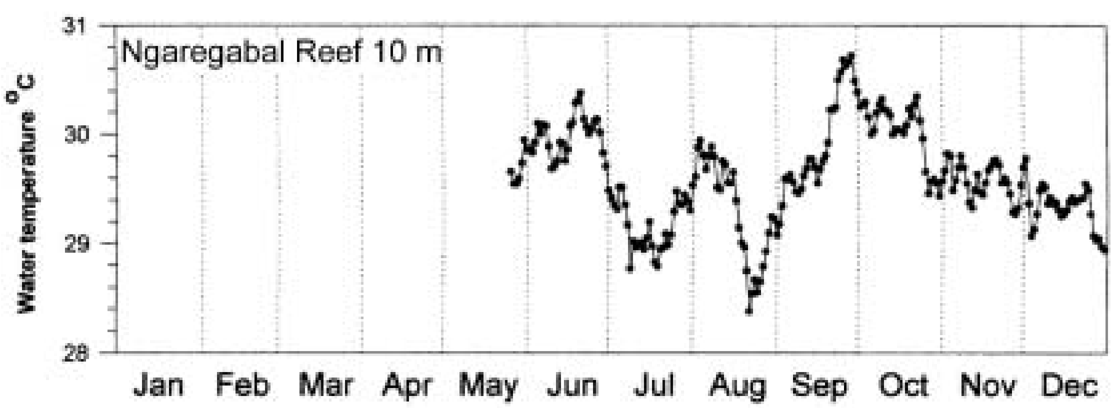

Figure 8. Daily mean water temperature at Ngaregabal Reef, Palau. Station established in May 2000.

The final lagoon reef presented, Falcon Reef, (Figure 9) is so named because it is the grounding site for a container ship, the Pacific Falcon, which ran up on this reef on 21 May 2000. This is an isolated patch reef mid-lagoon with no shallow water areas of any size near it. Thus, it is a useful area to assess the overall temperature regime of the lagoon away from the disturbing influences of shallow flats and island covers, which potentially have waters retained and heated during the day.

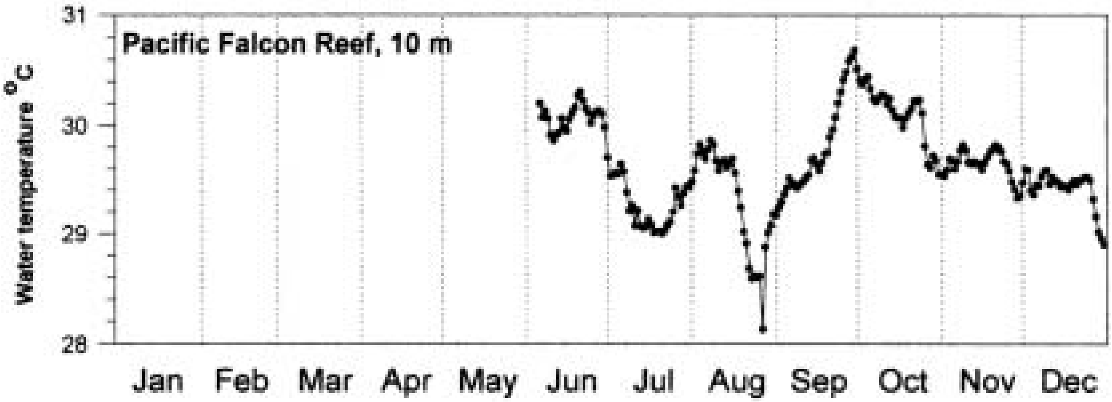

Figure 9. Daily mean water temperature at Falcon Reef, Koror, Palau. Station established in early June 2000.

On a day by day basis it also shows a tidal cycle to temperature, but the daily tidal excursion are less than either Malakal or Ngaregabal. This probably reflects its isolation from area where water can be quickly changed in temperature and reflects of general lagoon water temperature.

If we compare the three open lagoon stations, Malakal Harbor, Ngaregabal Reef, and Falcon Reef, (Figure 10) it is clear that Ngaregabal has the greatest daily variation in temperature, while Malakal Harbor is intermediate and Falcon Reef the lowest. Figure 10 is limited to only a single month (September 2000), but other months have similar patterns. Clearly there is both an isolation factor (distance from shallow water areas that might heat or cool more easily than the open lagoon) and closeness to the outside ocean factor (where ocean water would have an influence, probably moderating, on the temperature regime) for lagoon stations. Relying on a single station to give an overall picture of daily temperature dynamics in the lagoon would be risky, although all stations show the same annual cycle of temperature.

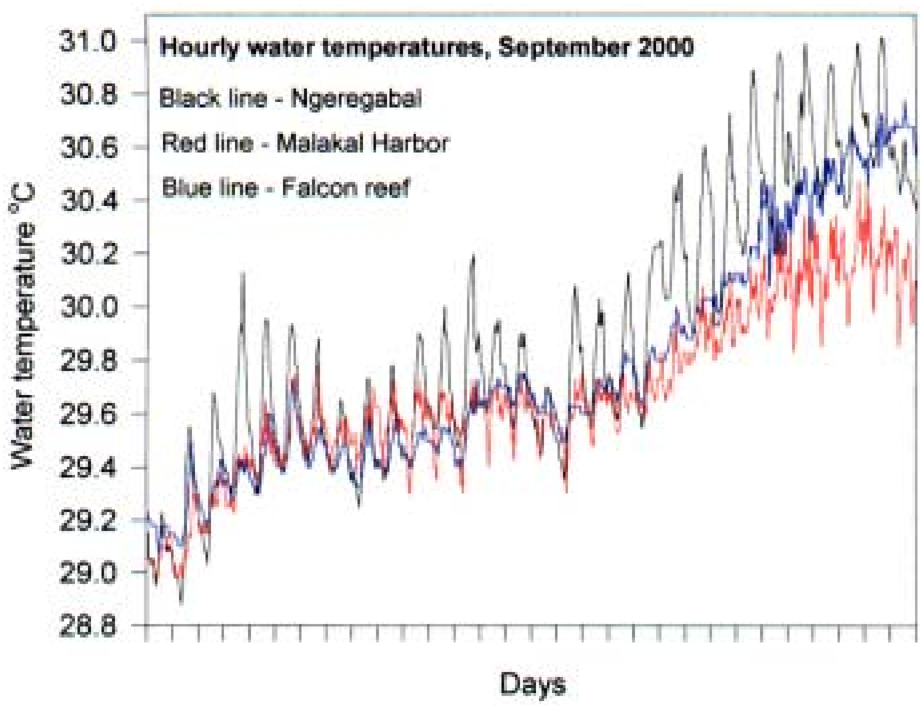

Figure 10. Daily variation in water temperature at three lagoon stations during September 2000.

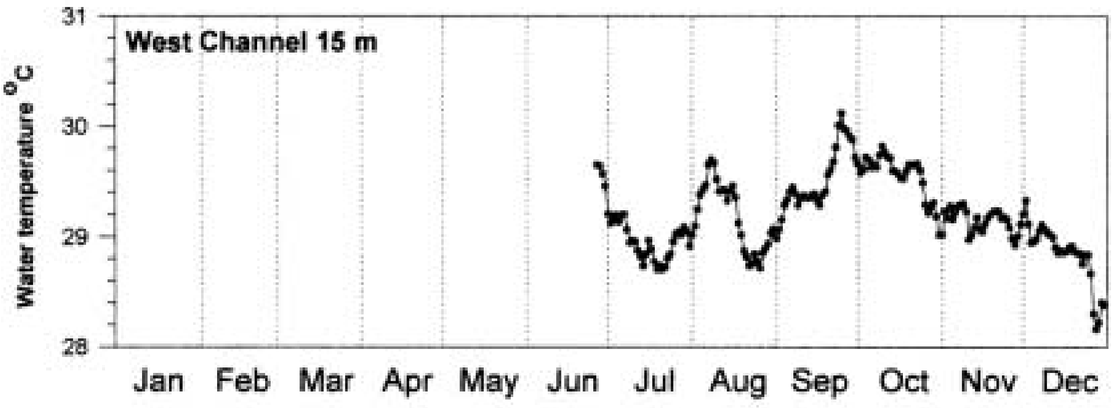

Figure 11. Daily mean water temperatures at the West Channel 15-m station for Year 2000. This channel is the major water exchange route between the western lagoon of Babeldaob and the open ocean.

The thermograph station located in the west channel (Figure 11), the major conduit between ocean and lagoon on the west side of Babeldaob, shows more thermal stability, over the year, than the lagoon stations. On a daily basis, the tidal signal is again very clear (Figure 12).

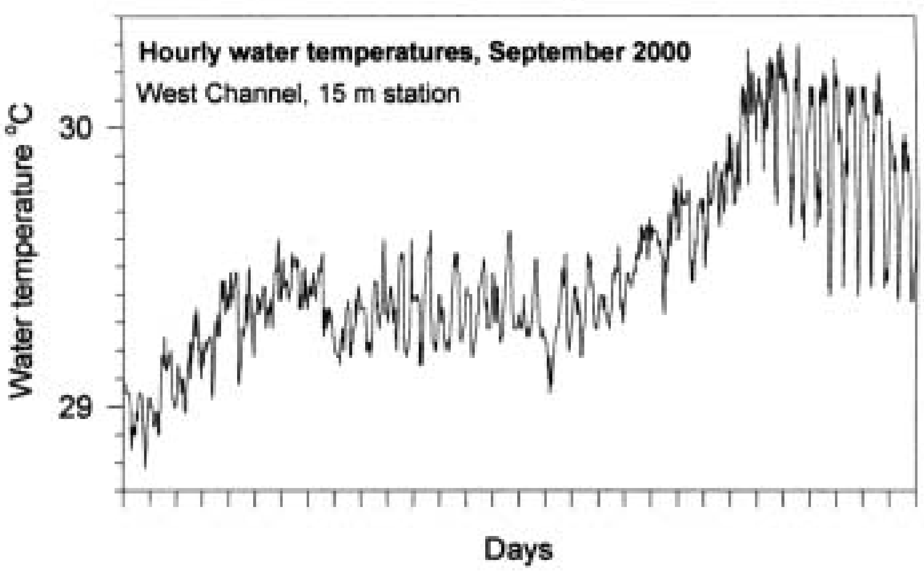

Figure 12. Hourly water temperatures at the West Channel 15 m station during September 2000. A tidal component of water temperature is clearly evident in this channel which has strong tidal currents.

The Short Drop Off site, on the eastern side of Palau, has a vertical array of six thermographs placed from 2 to 90 m deep. The station was originally started with three instruments, at 15, 55 and 90 m, with the other three others (2, 35 and 75 m) added in mid-2000. The mean temperatures at these depths for 2000 are shown in Figure 13. The 2, 15 and 35-m stations all had very similar temperature profiles over the year. The deeper stations (55, 75 and 90 m) showed decreasing temperatures with increasing depth, the expected picture, plus increasing seasonal variation in temperature with increasing depth. For example, the 55-m, 75 m and 90 m stations had respectively a 3, 4.5 and 5.5 ^{o}C range in weekly mean temperatures over the year. The weekly mean, however, masks great variation

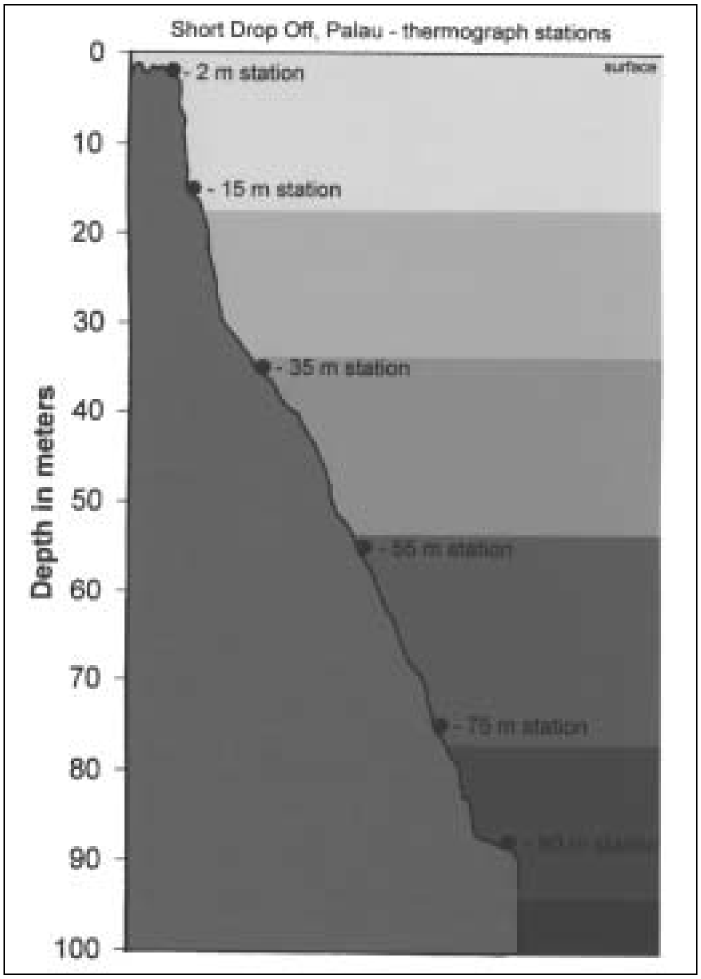

Figure 13. Profile of the Short Drop Off vertical thermograph array, with units at 2, 15, 35, 55, 75 and 90 m. The slope on the figure is not vertically exaggerated.

in day to day (even hour to hour) temperatures at the Short Drop Off site. The half hourly data indicated at 90 m temperature changes as great as 10°C in two hours. Overall temperatures are not stable at the deeper stations, as Figure 14 indicates. We would have to say that the deeper reef areas of Palau are a thermally dynamic environment.

The effect of these rapid swings in temperature on benthic marine life are not known, but potentially pose a significant physiological challenge to them. This has been discussed briefly in a short paper (Colin, in press). In general it appears the "sub-reef" environment of Palau, between about 60-75 m (200-250 feet) and 150 m (500 feet) is relatively depauperate. Considering both fishes and benthic invertebrates, it has been suggested temperature may be a limiting factor for these organisms. Certainly significant changes were seen in some benthic invertebrates during the last El Nino-La Nina cycle in Palau. In May 1997 (during the El Nino) water along this drop off was extremely cold by local standards and certain invertebrates were found at diving depths that had never been seen previously (Colin, 2000). However, one year later during the summer of 1998, water was extremely warm at depth, and these organisms, previously common, were not found in the same area (Colin, 2000). Monitoring of this vertical array continues and should provide some important insights into the movement of thermoclines between "normal" and ENSO cycle years.

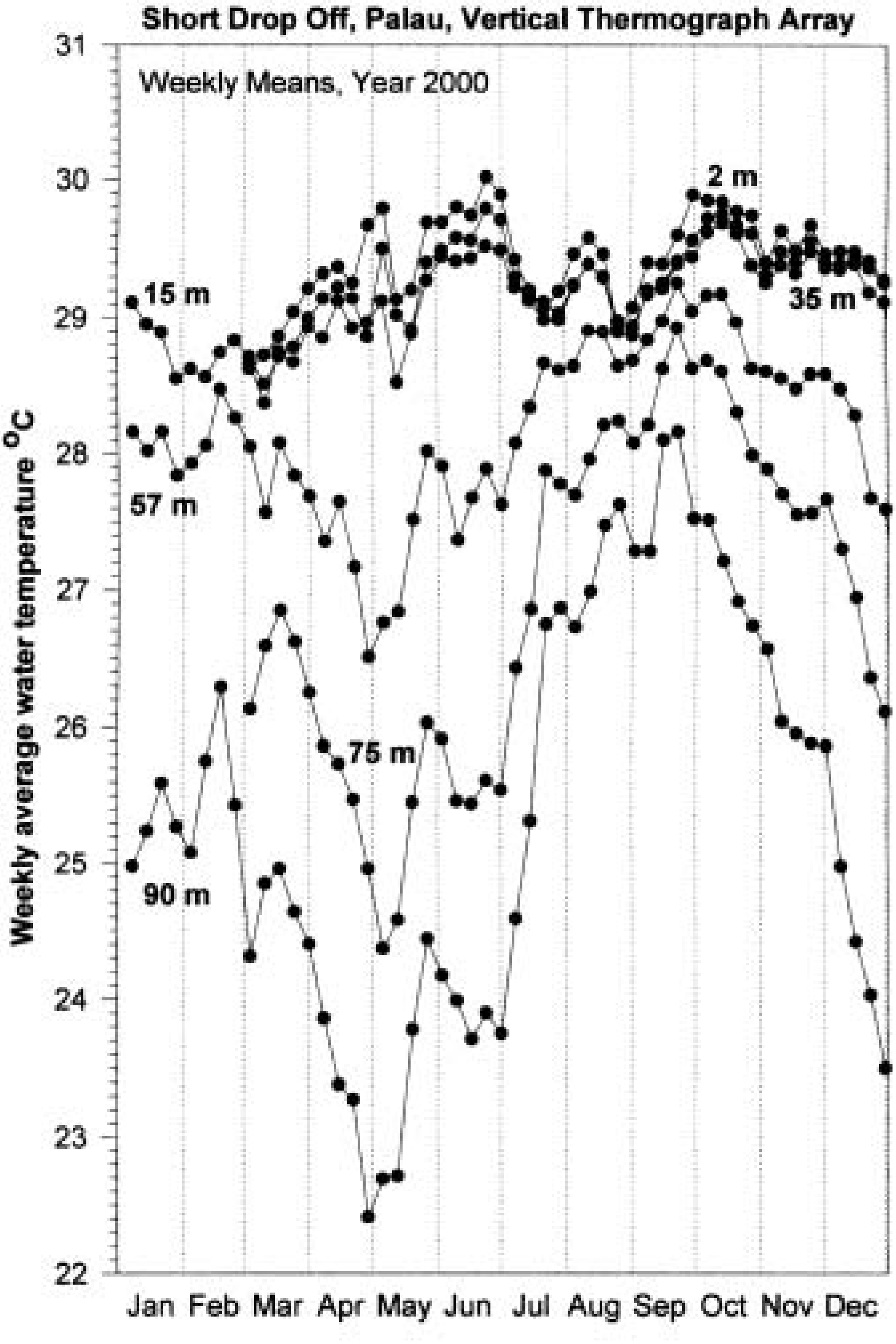

Figure 14. Weekly mean water temperatures at various depths on the Short Drop Off vertical thermograph array.

The relationship between weather conditions and water temperatures became more evident through the examination of the Year 2000 data. It was surprising to see that often times the summer period had decreasing water temperatures, often to a level at or below the winter "lows" (Figure 2 and others). Obviously it is not possible to generalize about winter having cooler water temperatures while summer is warmer. Overall we can say that during

2000 water temperatures ranged between about 28.5 and 30.5°C. Temperatures were a bit higher in some areas, but generally these ranges apply.

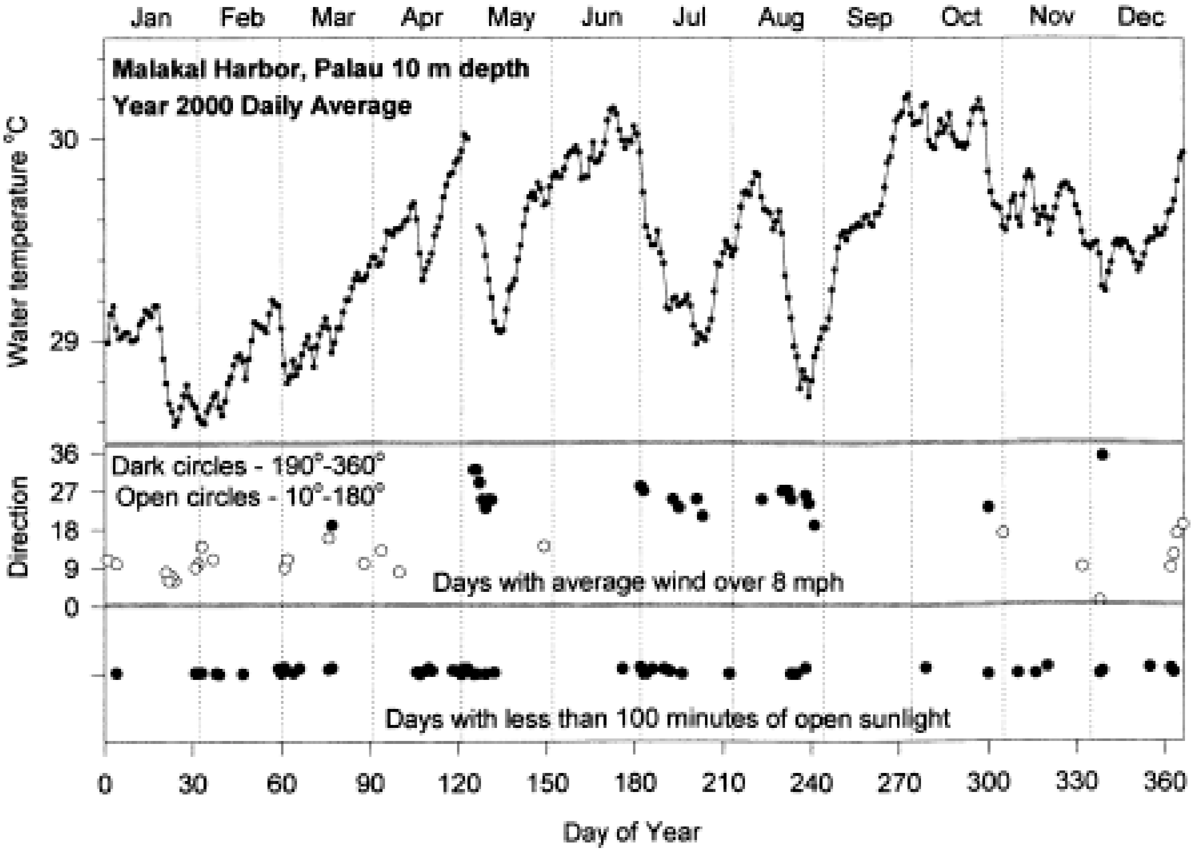

Figure 15. Daily mean water temperatures for Malakal Harbor during 2000 plotted against days when winds were greater than 8 MPH (12 KMH) from east or west and days with less than 100 minutes of open sunlight.

During the spring and summer there is a good correlation between weather events and decreases in water temperature. Figure 15 shows the occurrence of strong winds, by direction (east or west) and cloudy days (less than 100 min of open sunlight) from Palau Weather Station records compared with the water temperature curve of Malakal Harbor. Since all water temperature plots for the year show the same general pattern, we could use any of these, but chose the Malakal curve since it has been covered in some detail elsewhere in this document. The three longest periods of windy, cloudy weather associated with large drops in water temperature are during May, July and August. Such periods during the summer in Palau are associated with the western monsoon, which brings strong winds from the southwest and west along with heavy rain and clouds. While the association may be clear, what is actually causing the water temperatures to decrease is not certain. Possibilities include 1) wind induced upwelling from the cooler deeper water outside Palau, which is subsequently carried into lagoonal areas by the tides, 2) reduced solar radiation due to clouds causing temperatures to decrease or 3) increased wind producing higher evaporation and cooling of surface waters. These various factors are being further examined.

Theoretically, the question of whether upwelling is responsible for most of the temperature decrease can be addressed by looking at temperature stability in deeper water, below the first minor thermoclines. If upwelling is occurring, we should see a decrease in temperatures at a given depth over time. Figure 16 is similar to Figure 15, but has the daily mean water temperature at 35 m depth at Short Drop Off plotted. While the general trends in the yearly curve are the same, there is not as clear a temperature decrease with westerly winds as is evident in the Malakal data (Figure 15). Early May showed about a 1.5°C drop over about a week, while the July and

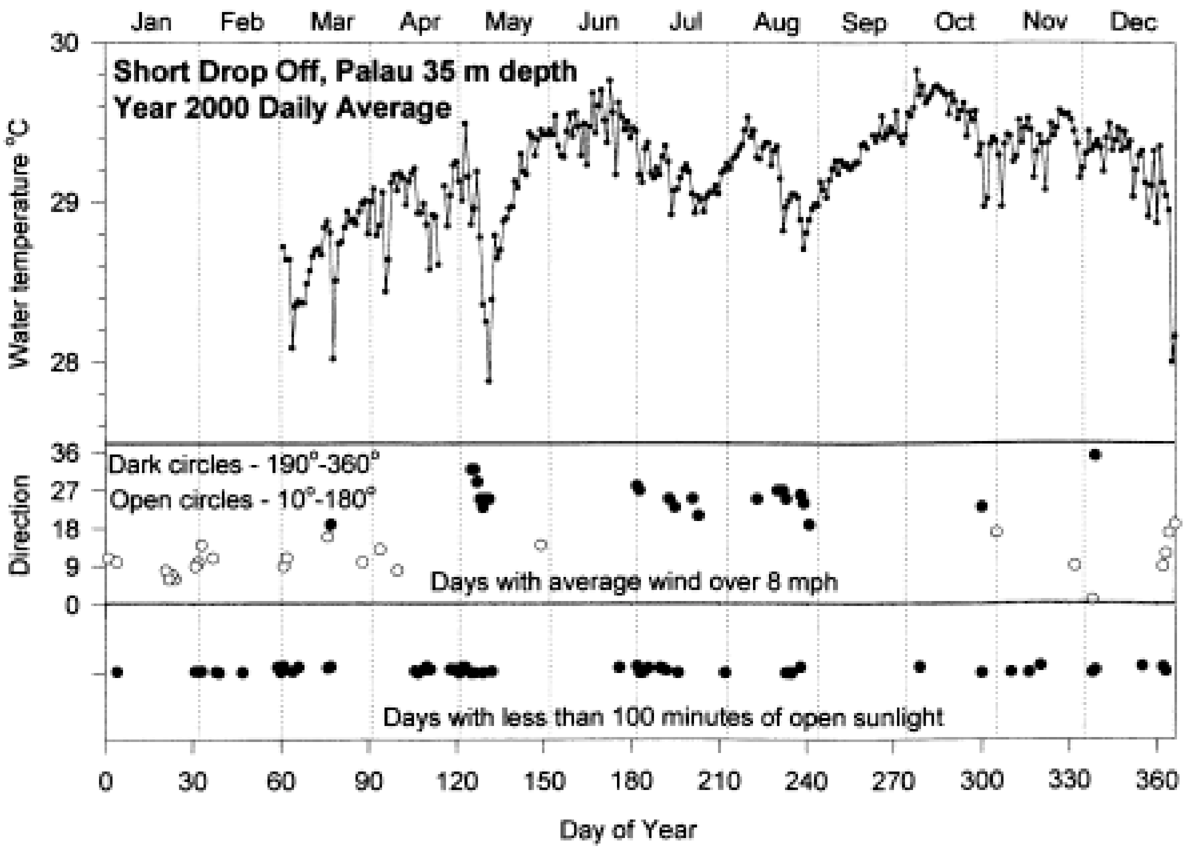

Figure 16. Daily mean water temperature at 35 m depth at Short Drop Off, Koror, Palau compared to strong winds from east or west and days with less than 100 minutes of open sunlight.

August periods showed a gradual drop of about 0.5°C. Deeper stations (55, 75 and 90 m) did not show a similar temperature drop at this time. The relative role of upwelling and temperature decrease for other reasons are receiving further attention and will be dealt with in more detail in subsequent reports.

The Short Drop Off thermograph array also allowed the examination of whether internal waves or tides were responsible for the rapid swings in water temperatures along the drop off there. Certainly the observed shifts in temperature at depth can be interpreted as internal waves. They are wave-form and cycle through over a period of several hours generally. Their association the tide in surface waters is not clear. Figure 17 shows water temperatures at 90 m depth compared with the tidal cycle on the surface for May 2000. The figure indicates the great and rapid variation in water temperature at this depth, and shows there is not an obvious correlation between temperature variation during any given day and whether the tides are spring or neap at that time. Compare this to Figure 6 for Malakal Harbor where there are distinct increases in water temperature range any day when there are spring tides compared to neap tide days.

The relationship between tides and water temperature cycling at depth is receiving further attention and will be dealt with more thoroughly in future reports. The role of these internal waves in potentially bringing nutrient rich deeper water into the relatively shallow coral reef environment may be very important.

There is, however, no obvious overall correlation between the state of the tide in the tidal cycle and water temperature. Any temperature within the normal range observed during the month could occur with any tidal height. This applies to both spring and neap tide days. Figure 18 shows the distribution of points for the two spring and two neap tide periods in May 2000 at 90 m depth at Short Drop Off. This rather simplistic comparison, however, may obscure some relationship between tide height and temperature over shorter cycles.

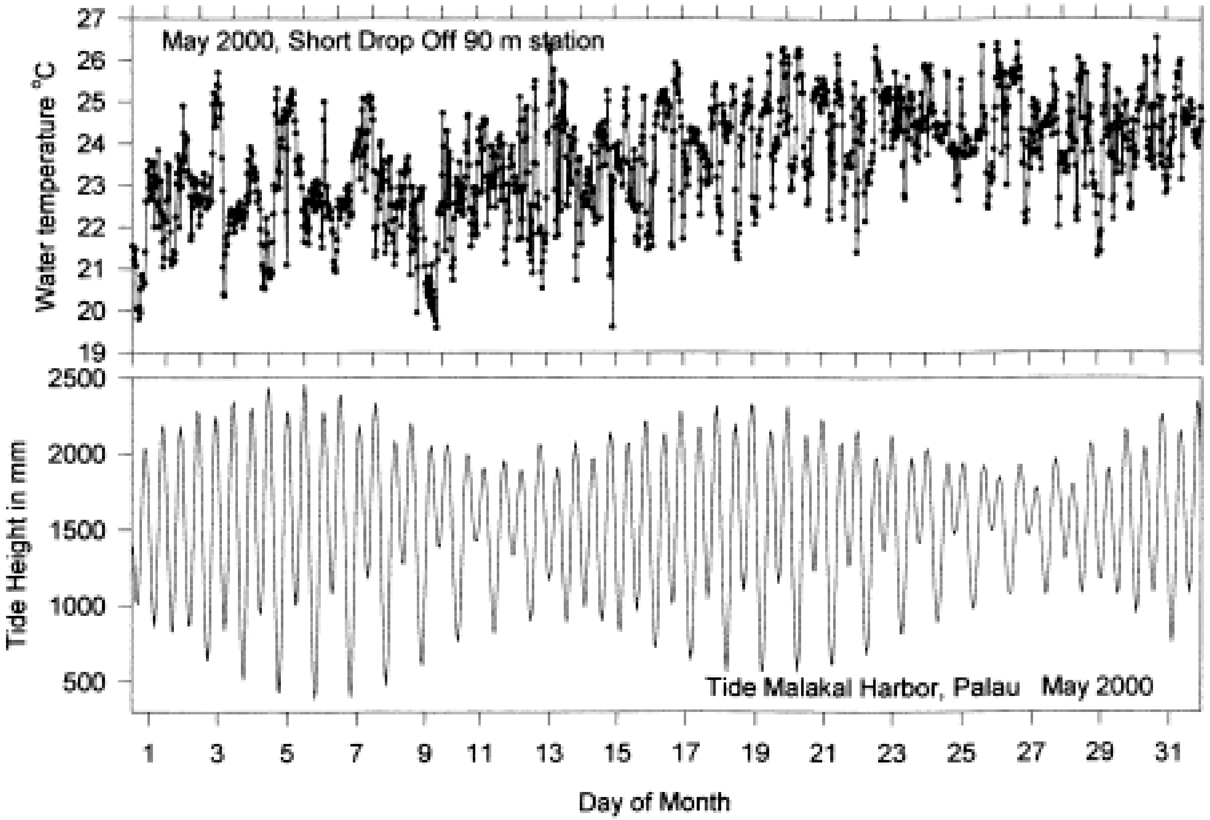

Figure 17. Comparison of half-hourly water temperatures (upper) at 90 m depth, Short Drop Off, Palau with surface tidal stage (lower).

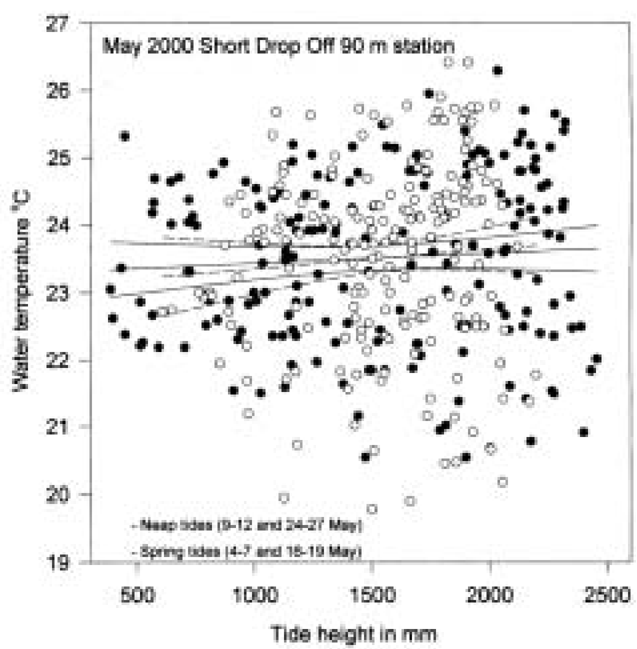

Figure 18. Relationship between tide height and observed temperatures at 90-m depth, Short Drop Off station on both neap (open circles) and spring tides (black circles).

A direct comparison was made between water temperatures observed via satellite and ground truth, where temperatures are directly measured by observers. Figure 19 shows the relationship between temperatures measured by mercury thermometer at irregular intervals at Short Drop Off, at the CRRF dock and for satellite-derived sea surface temperatures.

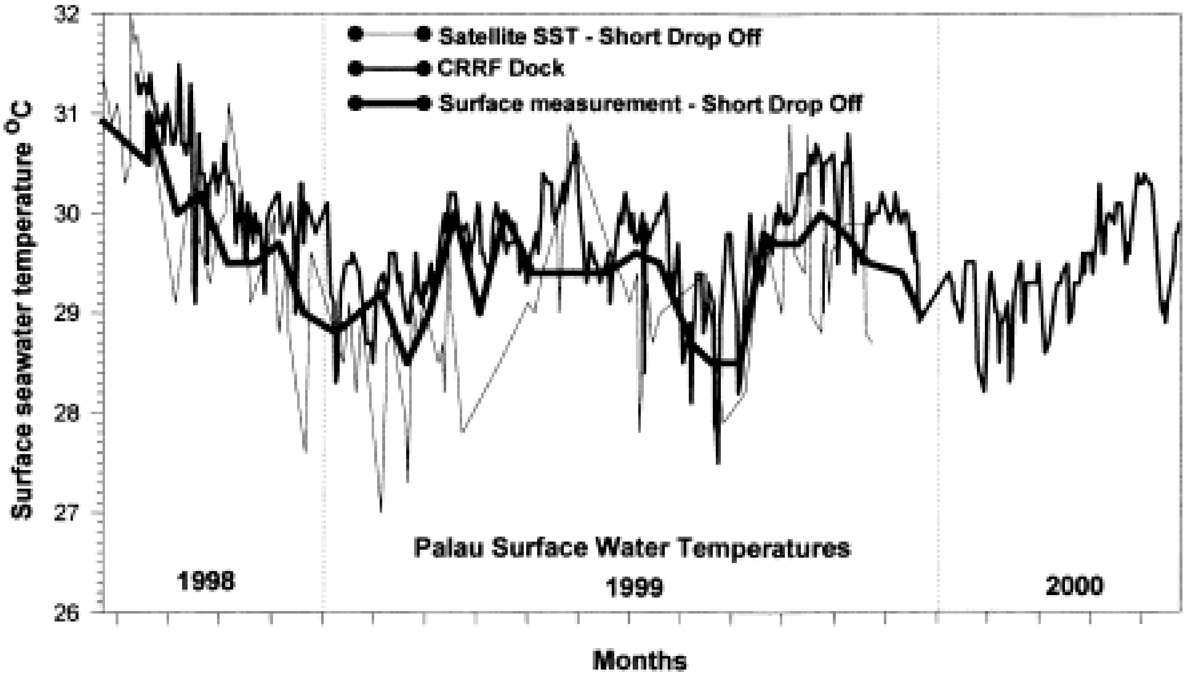

Figure 19. Relationship between satellite-observed sea surface temperature and ground truth temperatures for Palau.

Bruno et al. (2001) includes a fifteen-year retrospective look at Palau's water temperatures, based on satellite derived sea surface temperatures for two stations, one in the open ocean near the northern barrier reef and the second near the southern barrier reef. High water temperatures during the 1998 bleaching event are clearly evident, as well as earlier periods when temperatures climbed above the 29.55°C threshold of bleaching applied by Bruno et al. (2001).

Conclusion:

The Year 2000 has been a year in which water temperatures were generally within the range associated with healthy coral reefs and there was not any large scale bleaching along the Palauan reef tract during the year. Despite this generally favorable picture, there were times during the year when temperatures approached or briefly crossed the 30°C threshold. The 30°C level is perhaps more accurate in assessing the threshold point for coral bleaching in Palau, rather than the 29.55°C of Bruno et al. (2001). This report has also covered the last half of 1999 and a similar picture is seen from the data for that time period. There was a late summer peak in water temperatures, that apparently resulted in modest bleaching in some areas (to be covered in a subsequent Technical Report), but did not begin to compare the bleaching event during 1998.

The study has indicated some areas of the central lagoon, particularly in the Rock Islands near Koror Island can be somewhat warmer at any time than other lagoon areas by as much as 0.5°C. In lagoon areas the annual water temperature variation was only about 1.5-2.0°C, while the outer barrier reef was somewhat more stable with 1.0-1.5°C annual range. Surface water temperatures in inner lagoon areas can vary as much as 2°C during a single tidal

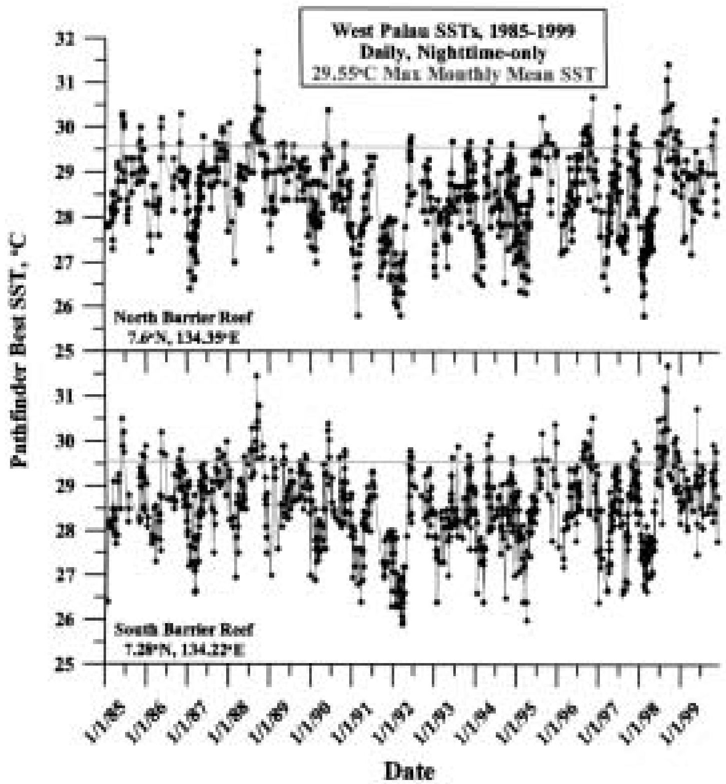

Figure 19. Satellite-derived sea surface temperatures for Palau 1985-1999, indicating years in which temperatures exceeded a 29.6^{o}C value, a possible threshold for coral bleaching. (From Bruno et al. 2001)

cycle, so caution must be used in interpreting thermal regimes based on single or few measurements, rather than a lengthy time series. There is also a clear coupling between tidal amplitude and daily (tidal) temperature variation

Perhaps the most surprising result of this study to date has been the realization that significant water temperature decreases can occur during late spring to fall, typically very warm months in Palau, which correlate closely with the occurrence of westerly monsoon winds and cloudy conditions. These temperature fluctuations occur throughout the reef tract.

The vertical arrays, originally established at Short Drop Off and subsequently expanded to Ulong Rock (and elsewhere in subsequent years) will provide valuable data on effect of climatic conditions on thermocline depth and behavior. The great daily and annual temperature range at depths below about 60 m in Palau imply that this "sub-reef" environment is perhaps thermally stressful (Colin, in press) and may effectively limit the benthic organisms occurring there. Some remarkable changes were noted in the fauna at 90 m depth along Short Drop Off between 1997 and 1998 (and later)(Colin, 2000). Unfortunately no thermographs were established along the reefs during the 1997-1998, so we are lacking both surface and deeper depth water temperatures of a definitive nature. This deficiency has hopefully been rectified, so that we will never lack for accurate temperature data to help understand what is occurring in reef environments throughout Palau.

This work in Palau has been assisting in refining the ability to measure sea surface temperature and predict coral reef bleaching based on satellite observations. The curves published in Bruno et al. (2001) are one of the first direct comparisons between actual reef temperature measurements and satellite estimates. Subsequent data are being used by NOAA NEDIS to refine models and produce even more accurate information from satellite observations.

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Appendix 1.

Latitude/Longitude for Water Temperature Monitoring Stations;

Ulong Rock (10 m sta)	7^o 17.425' N; 134^o 14.463' E
Ulong Rock (55 m sta)	7^o 17.453' N; 134^o 14.442' E
Short Drop Off	7^o 16.418' N; 134^o 31.440' E
Malakal Harbor	7^o 19.008' N; 134^o 27.627' E
CRRF Dock	7^o 20.283' N; 134^o 27.427' E
Ngerkuul Gap	7^o 19.170' N; 134^o 29.779' E
Ngaregabal Reef	7^o 24.725' N; 134^o 27.006' E
Falcon Reef	7^o 22.400' N; 134^o 23.240' E
West Channel	7^o 32.560' N; 134^o 28.059' E

Appendix II.

Water temperature data sets available Year 2000, archived with CRRF and GCRMN Micronesian node

CRRF Dock	Day 114 - end
Pacific Falcon reef	Day 157 - end
Malakal Harbor	All of year
Ngaregabal Reef	Day 146 to end, rest 1 hr interval!
Ngerkuul Gap	All of year
Nikko Bay	Day 150 - end
Ongael Basin	Day 150 - end
Short Drop Off 2 m	Day 60 - end
Short Drop Off 15 m	All of year
Short Drop Off 35 m	Day 60 - end
Short Drop Off 55 m	All of year
Short Drop Off 75 m	Day 60 - end
Short Drop Off 90 m	All of year
Ulong Rock 11 m	All of year
Ulong Rock 55 m	Day 154 - end
Ulong Rock 90 m	None
West Channel 15 m	Day 178 - end
West Channel 55 m	Day 178 - end