MONITORING AND CALIBRATING SEA SURFACE TEMPERATURE ANOMALIES WITH SATELLITE AND IN-SITU DATA TO STUDY EFFECTS OF WEATHER EXTREMES AND CLIMATE CHANGES ON CORAL REEFS

Thomas J. Goreau and Raymond L. Hayes
Global Coral Reef Alliance and Howard University

Keywords: Coral Bleaching, Global Warming, Sea Level Rise

ABSTRACT

Every major mass coral reef bleaching event since 1983 followed a warm season +1 degree Celsius anomaly, as recorded in NOAA global sea surface temperature data. Comparison of low resolution blended satellite and ship data bases averaged over the broadest time and space scales, high resolution satellite data, and in-situ measurements in the Caribbean showed that high resolution data was within around 0.2 degrees of the real value, but underestimated it increasingly as temperature rose. In contrast, low-resolution data for the Caribbean systematically underestimated temperatures by up to several degrees, in a site-specific manner. The bias appears greatest for large or high islands and for continental shorelines where topographic thermal convection effects cause high generation of small clouds, which cause satellite temperature measurements to be too low. Although low-resolution data are adequate to identify large-scale temperature anomalies in the Indo-Pacific, they miss small, intense, transient thermal anomalies and therefore underestimate actual thermal stress. Despite these limitations, combining remote sensing data and field observations suggests that current climatic extremes are adequate to trigger coral bleaching, placing coral reefs worldwide at severe risk from any further global warming.

MASS CORAL BLEACHING EVENTS

Coral reef ecosystems provide the major source of marine biodiversity, productivity, fisheries, shore protection, and sand generation for over 100 countries, making them among the most economically valuable ecosystems in terms of income generation and in terms of replacement costs or damages if these natural ecosystem functions are lost or damaged. Coral reef ecosystems are based on the unique ability of corals to build wave resistant structures which provide the habitat for all other reef organisms, and this ability is dependent on corals having a healthy population of symbiotic unicellular algae, or zooxanthellae, in their tissues. The symbiotic algae provide the coral with most of its food, its ability to grow rapidly, and its color: Under conditions of sublethal stress, regardless of the cause, corals expel their symbiotic algae and lose their color, allowing the white skeleton to be seen through the transparent tissue. This is misleadingly called "bleaching" because such corals superficially resemble those whose tissues have been digested by bleach solutions.

Mass bleaching of coral reefs, on scales of thousands of kilometers, was first reported in the early 1980s, and has since appeared almost every year and in almost every major reef region (Williams & Bunkley-Williams, 1990; Glynn, 1991; Goreau & Hayes, 1994). Prior to the 1980s all, known bleaching events were local in extent, and clearly due to local stresses. These commonly were due to 1) local heating caused by poor circulation in tide pools and lagoons with restricted circulation during low tides occurring during periods of bright sunshine, 2) fresh water and mud stress to shallow reefs immediately down-current from rivers swollen by hurricane floods, and 3) high temperature saline effluents from desalination plants or water used to cool nuclear power plants. For the first two types of stress bleaching was seen only in locally stressed areas, and recovery was generally rapid once the transient stress was removed. In the case of thermal effluents stresses are permanent, corals bleached and died, and these zones show no sign of recolorization by new coral colonies with higher temperature tolerance, even after 20 to 30 years. Mass bleaching events of the 1980s and 1990s differ from local bleaching events in taking place over large regions synchronously, and bearing no relationship to any known local stress.

Wherever mass bleaching occurred, local observers noted no unusual stresses, except that bleaching immediately followed unusually long periods of high air temperature, high sunshine, low winds, and low clouds. Almost all reported that high water temperature was the most likely cause (Williams, Goenaga, & Vicente, 1987; Goreau, 1990; Goenaga & Canals, 1990; Williams & Bunkley-Williams, 1990; Jokiel & Coles, 1990; Goreau et al., 1993; Goreau & Hayes, 1994). At almost all sites there was little or no long term in situ temperature data available which would allow determination of whether temperatures where in fact anomalously high, and a number of other alternative causes of bleaching were proposed, such as stress from ultraviolet light or pollution. However all alternative explanations are inconsistent with field and laboratory evidence. The distribution of mass coral bleaching is entirely unrelated to pollution or salinity gradients, and while corals exposed to high light levels bleach more rapidly than those in dim light, bleaching only takes place above a threshold temperature. Corals show little depth gradients in bleaching that would be expected if ultraviolet light were the cause, and in addition corals are superbly adapted to ultraviolet light stress through their ability to make ultraviolet screening pigments. These screening pigments are contained within the coral tissue, and remain after the algae are expelled, so that even bleached and transparent coral tissue is observed to be opaque to ultraviolet light (C. Mazel & T. Goreau, unpublished observations). These observations suggest that ultraviolet light is capable of providing additional stress but is not the major trigger mechanism for mass coral bleaching. However since rapid warming of the ocean is facilitated under calm clear conditions which allow maximum light penetration, these two factors tend to co-vary. Ultraviolet light exposure is thought to be increasing in polar and temperate regions due to decrease in the total concentration of stratospheric ozone, but there has been little or no significant decrease in total ozone over the tropics. On the other hand the global warming recorded over the past 150 years has taken place in both tropical and cold ocean regions. Carbon dioxide cannot be the trigger because CO_2 is more concentrated in northern latitudes due to more fossil fuel combustion, but bleaching takes place in both hemispheres. Furthermore CO_2 is lowest in the summer months when bleaching takes place, due to uptake by forests, and highest in winter when respiration dominates.

To determine whether mass bleaching is related to temperature anomalies in the absence of long term local temperature records, we examined consistent NOAA global sea surface temperature data bases derived from satellite and shipboard observations, in order to see if they accurately identify ecosystem thermal stress patterns preceding bleaching events. Because published sea surface temperature data bases differ in the types of measurements used and in the time and space scales over which they are averaged we have used two different databases. The first, based on satellite measurements recorded twice per week at 4 kilometers resolution, is used for the Gulf Stream Ocean Features Analysis in NOAA's Oceanographic Monthly Summary. The second, published in NOAA's Climate Diagnostics Bulletin, is based on monthly averages of blended satellite and oceanographic data with an effective spatial resolution of several hundred kilometers (R. Reynolds, NOAA, personal communication).

CALIBRATION OF HIGH RESOLUTION SATELLITE SST DATA

The data used here is based on analysis of Advanced Very High-Resolution Radiometer (AVHRR) satellite images in the thermal infrared channel available as gray scale photographs with 4 kilometer pixels. These are converted to temperatures using a calibration scale. A crucial feature of the analysis is that it is done by a human observer, who visually identifies regions that appear to be completely cloud-free (J. Clarke, NOAA, personal communication). This is critical, because the presence of clouds in the pixel contaminates the sea surface temperature signal with the lower values characteristic of cloud tops. Large clouds, such as those associated with weather fronts, are readily visible in the images and avoided, however the major problem is the possible presence of sub-pixel size clouds which cannot be seen in the images, but which are nevertheless capable of adding a spurious signal. This is especially a problem in the tropics, where clouds tend to be small. Human judgement is used to identify those pixels which are likely to be cloud-free because their temperatures represent a consistent regional maximum background value. There is always a finite, but small, chance that all such pixels may be subject to hidden contamination from widely dispersed small clouds, which would tend to result in an underestimate of the true value. The resulting spot temperature readings, recorded twice a week for ten years, were used to develop monthly average sea surface temperature records for 7 sites around the Caribbean: Puerto Rico, Jamaica, Cayman, Cozumel, Florida Keys, Nassau, and Bermuda (Goreau et al., 1993).

Although the calibration scale used to assign temperatures to the gray scale radiometer images is based on comparison of satellite-derived values with direct oceanographic measurements, these values have generally been regarded as only rough estimates of actual sea surface temperatures. Water is opaque to infrared radiation, so the signal measured by the satellite radiometer is emitted by a surface layer only a few millimeters thick, which may be unrepresentative of bulk surface water temperatures under conditions with strong vertical near-surface temperature gradients. These can be found following heavy rains when a surface layer of cooler fresher water may float on top of warmer sea water, or under intense evaporation where a hot surface layer may overlie cooler water. Such stratification is likely only under extremely calm conditions where molecular diffusion prevails, because wind and wave mixing homogenizes surface layers on much longer length scales than the infrared thermal skin depth. Nevertheless, uncertainty over accuracy of satellite data has inhibited its use in assessing local climate patterns that may have ecological significance.

In order to determine if the satellite-derived sea surface temperature values are accurate, the monthly average values were compared with in-situ data. A time series of 65 monthly measurements of ocean temperature were directly recorded with calibrated mercury thermometers at a depth of 5 meters below the surface on the fore reef at Discovery Bay, Jamaica by T. Goreau and R. Gates. The time series covers more than five years, from January 1985 to March 1990. These results (Figure 1) show that the high-resolution data is strongly correlated with in-situ measurements at this site:

1) $T_{sat} = 1.998 + 0.920\ T_{meas}$

$R = 0.897$ $P < 0.001$ $n = 65$,

where Tsat is the satellite derived value, Tmeas is the measured value, R is the correlation coefficient, P is the probability of the correlation emerging by chance, and n is the number of comparisons.

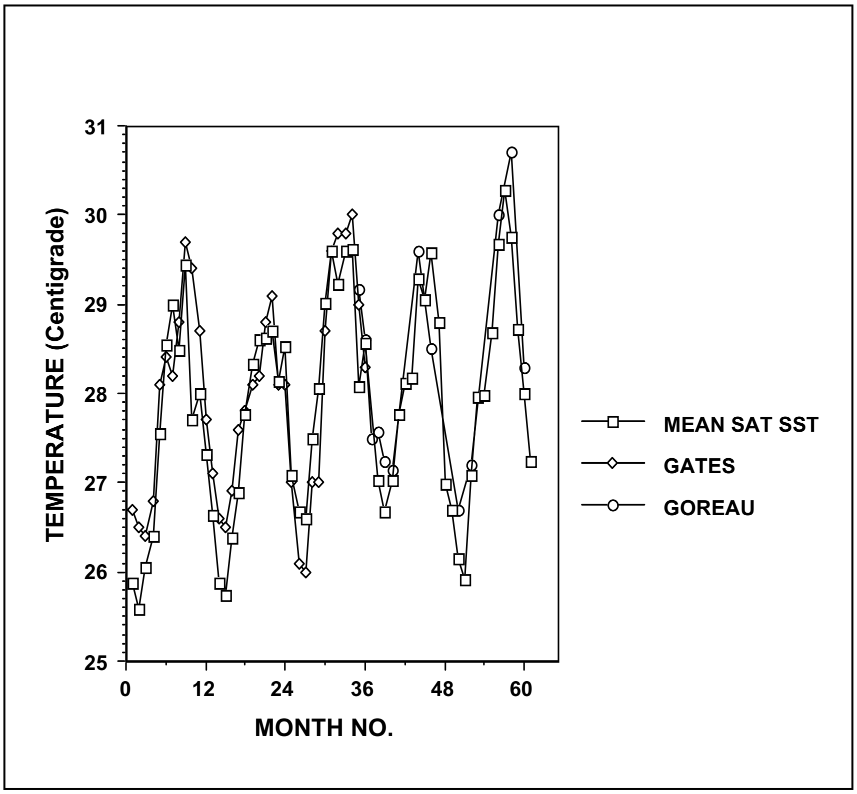

Figure 1 Comparison of high resolution satellite sea surface temperature data for the North Coast of Jamaica (solid line) with in-situ measurements at Discovery Bay (dashed lines) for 1985 - 1989.

In general, satellite derived values were within about 0.2 degrees of the correct value, but generally underestimated it by a value that increases as temperature rises. For example when the correct value is 26.0 degrees the satellite underestimates it by 0.08 degrees, and when the correct value is 30.0 degrees the satellite underestimates it by 0.40 degrees. This trend is expected since increasing temperature causes increased evaporation, thermal convection, and small cloud formation, which results in increasing sub-pixel scale contamination of the sea surface temperature radiometer signal, providing temperature estimates which are systematically too low under the warmest conditions. Such conditions promoting formation of small clouds are most likely near continental coastlines, near large or mountainous islands, and in regions with complex ocean current flows and strong offshore temperature gradients.

Similar calibration results to those from Jamaica were obtained comparing satellite data with two years of in-situ data from Grand Cayman. Comparison of the satellite-derived record for the north coast of Puerto Rico with values measured in situ in the reefs of La Parguera, on the south coast, gave virtually identical values (A. Winter, University of Puerto Rico, personal communication). More sophisticated analysis using temperatures derived from night time satellite passes gives values within about 0.1 degrees celsius of values measured by moored oceanographic recording instruments near Bermuda (Gleeson & Strong, 1994). It therefore appears that high-resolution AVHRR data provides values that are sufficiently accurate to be useful in estimating thermal conditions in reef ecosystems.

A further caveat is necessary. Satellite derived sea surface temperatures represent offshore, open ocean conditions, and will not be the same as values in the reef habitat wherever restricted circulation and coastal freshwater inputs are found. Shallow waters in and behind coral reefs can both heat up and cool down more rapidly than open ocean waters whenever water flow is low due to currents or tidal flows. As a result the actual temperature experienced by corals may differ from values in the open ocean. Therefore the results derived from remote sensing should be applied only to corals in fore reef habitats which are exposed to open ocean waters. Corals in back reef habitats will generally be exposed to higher maximum temperatures due to restricted water circulation.

CALIBRATION OF LOW RESOLUTION BLENDED SST DATA

Global monthly average sea surface temperature data is based largely on satellite data, but blended with high precision oceanographic data where available, are also available from NOAA. The algorithms used in processing this data set effectively average the data over several degrees of latitude and longitude, producing an effective pixel size up to 400-600 kilometers in size (R. Reynolds, NOAA, personal communication). Thus the data cannot be expected to be accurate in regions of complex current flow on smaller scales, such as occurs around many Caribbean islands. On the other hand they may be more representative in the Pacific and Indian Oceans, where conditions are often uniform on much larger spatial scales.

Monthly average sea surface temperature anomalies recorded in the low-resolution data set were compared with the values from the high resolution data set for seven Caribbean locations. Linear regression analysis yielded the following results for the best linear fit,

2) $T_L = A + B \times T_H$

where T_L is the low resolution estimate, T_H is the high resolution estimate, A is the intercept, and B is the slope:

LOCATION	A	B	P	R^2
PUERTO RICO	.01710	.70327	.021	.37
JAMAICA	.09011	.38738	.040	.31
CAYMAN	:05747	.26902	.127	.17
COZUMEL	+.04889	.92822	.014	.41
FLORIDA KEYS	.06821	.21008	.173	.09
NASSAU	+.08907	.07402	.772	.01
BERMUDA	+.21782	.80987	.001	.61

R2 is the square of the correlation coefficient, an estimate of the fraction of variance that the regression explains, and P is the probability that this relationship could be due to chance.

If the values of temperature in the two data sets were identical, A would be zero, B would be one, P would be zero, and R^2 would be one. All sites have slopes with values less than one, indicating that the low-resolution data underestimate temperature increasingly as positive temperature anomaly increases. The low resolution estimate is very strongly significantly related ($P = 0.001$) to the high resolution estimate in Bermuda, is significantly related ($P < 0.05$) to it in Puerto Rico, Jamaica, and Cozumel, and is not statistically significantly related ($P > 0.05$) to it in Cayman, Florida, and Nassau. In several sites the low-resolution data entirely failed to record large positive temperature anomalies seen in the high-resolution data and in the field measurements, underestimating actual values by up to 2 degrees. It therefore appeared that the low-resolution data gave positive temperature anomaly values that were systematically too low, but to a degree which was site specific. As a result, the low-resolution satellite data is regarded as unreliable in parts of the Caribbean. Sites where the low-resolution data are least reliable at identifying hot spots showing up in high-resolution data appear to be those subject to strong locally generated cloud formation.

Despite these first discouraging results from the low-resolution data in the Caribbean, a check was nevertheless made in the low-resolution data for bleaching related positive sea surface temperature anomalies in the Pacific and Indian Oceans. Unexpectedly, the low resolution data yielded the identical results in the Pacific and Indian Oceans that high-resolution data produced in the Caribbean: it showed each mass bleaching event followed a warm season positive temperature anomaly of around one degree Celsius for a month, or more (Goreau & Hayes, 1994). As bleaching in coral reefs around the world follows similar temperature anomalies, the low-resolution data is generally adequate to identify "hot spots" capable of inducing bleaching in the Pacific and Indian Oceans, even though higher resolution data is needed for the Caribbean, and possibly some sites near ocean margins. The low-resolution data turns out to be more useful than anticipated for monitoring bleaching in most of the world's coral reefs. However it is likely to underestimate actual thermal stresses since very small, intense, and rapidly moving anomalies could be missed.

CORAL BLEACHING AND WEATHER ANOMALIES

Comparison of high-resolution Caribbean sea surface temperature records with observations of bleaching showed that at each site there was a minimum monthly average temperature above which mass bleaching always followed, and below which it never was reported (Goreau et al., 1993). This critical value was strongly dependent on mean annual temperature, with result that the same coral species bleach at cooler sites at temperatures that would not cause bleaching in warmer locations. Nevertheless at all sites corals bleached whenever they were affected by temperature excesses of around 1.0 degrees Celsius above the average value of the warmest month.

Although low-resolution data did not show the Caribbean hot spots seen in the high-resolution data during bleaching years, a search of low-resolution global sea surface temperature anomaly data in the Pacific and Indian Oceans showed that every mass bleaching event reported in those areas also followed a +1.0 degree hot spot in the warmest months (Goreau & Hayes, 1994). Anomalies of this magnitude at cooler times of the year did not precede bleaching. Following intense bleaching and hot spots in all three oceans during 1991 (Goreau & Hayes, 1994), hot spot anomalies of sufficient magnitude, timing, and location to cause mass bleaching did not occur for a three year period after the eruption of Mount

Pinatubo in the Phillipines. The high altitude sulfuric acid aerosols produced by this volcano reflected sunlight back out to space and cooled the entire earth during the three years it took them to settle out. Except for small hot spots that caused fairly mild bleaching in Jamaica, Florida, and the Bahamas, there were no mass bleaching events reported anywhere. During this interval coral degradation from human activities such as pollution, sedimentation, eutrophication, dredging, overfishing, etc. continued to increase, but these stresses were not reported to cause mass bleaching.

Only in early 1994 did hot spots sufficiently located and timed to cause bleaching appear. They were associated with bleaching in the Pacific, Indian, and Atlantic Oceans (Goreau & Hayes, 1995b). A detailed study of NOAA sea surface temperature data at 37 locations across the Pacific, Indian, and Atlantic oceans for 1993 and 1994 included sites at which bleaching took place, where it did not and would have been reported had it taken place, and where no information was available. Although there was no statistically significant difference in the maximum monthly average temperature at sites where bleaching took place and where it did not, bleaching sites had statistically significantly higher positive temperature anomalies. All sites where bleaching was certainly not present had maximum temperatures no more than +0.9° Celsius above average, while almost all bleaching sites had anomalies of +1.0° C or more in the warmest month. Only three sites where bleaching occurred had anomalies below +0.9° C according to the satellite data, however all were in locations where there are complex current flows and temperature gradients around very cloudy mountainous shores where the low resolution data would be most expected to underestimate actual stresses. One site, Tutuila, Samoa had an anomaly recorded of +0.8° C, but it is a high island which is exceptionally cloudy, and in-situ data indicated that the satellite values were too low by up to a degree. The other two sites were located along the mountainous Brazilian south coast, with cool offshore currents. Bleaching corals were located in warmer inshore habitats which in situ measurements showed to be more than a degree warmer than the values from the remote sensing data (A. Migotto, Universidade de Sao Paulo, personal communication). While use of the 1.0° C anomaly from low resolution data to predict bleaching is successful at predicting most sites it misses some events because it underestimates temperatures at some hot locations where bleaching was reported and where higher temperatures were shown to be present by in-situ measurements.

CORAL BLEACHING, GLOBAL WARMING, AND SEA LEVEL RISE

Remote sensing data appears adequate to confirm that current hot weather anomalies are adequate to trigger mass bleaching in coral reef ecosystems. This suggests that these ecosystems are already at or near their maximum temperature limit everywhere, and cannot withstand any further warming from global climate change (Goreau & Hayes, 1994). The goal of the Framework Convention of Climate Change, signed at the Earth Summit in Rio de Janeiro in 1992, is to limit the rate of global climate change to a level which preserves the critical elements of the Earth's natural biosphere, atmosphere ocean system, including the most climatically sensitive ecosystems. Unfortunately it failed to identify such ecosystems, or require their monitoring for signs of climate stress, nor require mechanisms to control net greenhouse gas emissions to requisite levels.

Global sea surface height measurements recently taken by the TOPEX/Poseidon satellite showed that sea level is rising by 2-3 millimeters per year. This level is close to the maximum rate at which coral reef frameworks can grow vertically. Thus only the very healthiest reefs could be expected to keep up with this rate, and would fail if it were to increase. Bleached corals either die if the temperature stress is excessive (Salvat, 1992), or completely cease upward growth while they undergo a bleaching and recovery period if the stress is mild (Goreau & Macfarlane, 1990). Any continuation of bleaching at the current level or an increase will render many reefs completely unable to deal with current rates of sea level rise, much less any future increase. Consequently coral reefs are the most threatened ecosystem from the point of view of both sea level and temperature rise, being at their current limits with regard to both factors.

ACKNOWLEDGEMENTS: We thank Ruth Gates for supplying a portion of the temperature measurements used from Discovery Bay, Jennifer Clarke for providing the NOAA high-resolution satellite data maps, and Richard Reynolds for discussion on spatial averaging in NOAA SST data processing algorithms.

REFERENCES

Gleeson, M.W. and A.E. Strong, *Applying MCSST to coral reef bleaching*, COSPAR 94, A1 085, Hamburg,Germany (1994).

Glynn, P.W., Coral reef bleaching in the 1980s and its possible connections with global warming*, Trends Ecol. Evol.,* **6,** 75-179 (1991).

Goenaga, C. and M. Canals, Islandwide coral bleaching in Puerto Rico , *Carib. J. Sci.,* **26,** 171-175 (1990).

Goreau, T.J., Coral bleaching in Jamaica, *Nature*, **343,** 417 (1990).

Goreau, T.J. and A.H. Macfarlane, Reduced growth rate of Montastrea annularis following the 1987-1988 coral bleaching event*, Coral Reefs*, **8,** 211-216 (1990).

Goreau, T.J. and R.L. Hayes, Coral bleaching and ocean "hot spots", *Ambio*, **23,** 76-180 (1994).

Goreau, T.J. and R.L. Hayes, Monitoring and calibrating sea surface temperature anomalies using satellite and in-situ data to study the effects of weather extremes and climate changes on coral reefs, *Proc. Conf. Remote Sens. Environ. Monit. Sust. Devel. Amer*., San Juan, PR (1995a).

Goreau, T.J. and R.L. Hayes, A survey of coral reef bleaching in the South Central Pacific during 1994, *Global Coral Reef Alliance*, pp. 200 (1995b).

Goreau, T.J., R.L. Hayes, J.W. Clarke, D.J. Basta and C.N. Robertson, Elevated sea surface temperatures correlate with Caribbean coral reef bleaching, pp. 225-255 in R.A. Geyer (ed.), *A Global Warming Forum: Scientific, Economic, and Legal Overview*, CRC Press, Boca Raton, FL (1993).

Hayes, R.L. and T.J. Goreau, Tropical coral reef ecosystem as a harbinger of global warming, *World Res. Rev.,* **3**(3), 306-322 (1991).

Jokiel, P.L. and S.L. Coles, Response of Hawaiian and other Indo-Pacific corals to elevated temperatures*, Coral Reefs*, **8,** 155-162 (1990).

NOAA Climate Diagnostics Bulletin, Washington DC.

NOAA Oceanographic Monthly Summary, Washington DC.

Salvat, B. Blanchissement et mortalite des scleractinaires sur les recifs de Moorea (Archipel de la Societe) en 1991, *Compt. Rend Acad. Sci*., Paris, **314,** 105-111(1992).

Williams, E.H. and L. Bunkley-Williams, The world-wide coral bleaching cycle and related sources of coral mortality, *Atoll Res. Bull.,* **335,** 1-71(1990).

Williams, E.H., C. Goenaga, and V. Vicente, Mass bleaching in Atlantic coral reefs, *Science*, **238,** 877- 878 (1987).