THE ROLE OF OCEANOGRAPHIC CONDITIONS AND REEF MORPHOLOGY IN THE 2002 CORAL BLEACHING EVENT IN THE NORTHWESTERN HAWAIIAN ISLANDS

BY

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ABSTRACT

Researchers on two research cruises to the Northwestern Hawaiian Islands (NWHI) in September 2002 recorded widespread massive coral bleaching, particularly at Kure, Midway, and Pearl and Hermes atolls at the northern end of the Hawaiian Archipelago. While details of the coral bleaching and biological impacts are presented by Kenyon et al. (in review), this work is focused on the contributions of broad-scale meteorological and oceanographic conditions, as well as the local effects of reef morphology, to the severity and distribution of the observed coral bleaching.

Anomalously high regional sea surface temperature (SST), identified as the primary proximate factor in the bleaching event, was related to a band of quiescent winds and high insolation intersecting the northern end of the Hawaiian Archipelago. These conditions were in turn related to a variable ridge of high atmospheric surface pressure present both immediately preceding and during the event. Atoll/reef morphology and circulation patterns inferred from *in situ* observations are used to explain localized elevation of SST within the three northernmost atolls which increased the severity of bleaching within lagoon and backreef habitats.

A method of predicting overall differences in bleaching between adjacent reef groups in the absence of detailed *in situ* temperature data is presented. This method relies on regression of lagoon and backreef volumes and satellite SST to describe observed coral bleaching.

INTRODUCTION

Mass coral reef bleaching events, when significant numbers of corals in a reef system expel their symbiotic zooxanthellae, often lead to major coral mortality and decreased coral cover. Although many other local stressors to coral reefs worldwide also have been documented, coral bleaching has been identified as globally significant and arguably the major worldwide threat to coral reefs (Hoegh-Guldberg, 1999). Determining

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an area's susceptibility to bleaching through identification of causal factors in the context of climate change is a key to designing successful refugia for coral reefs (West and Salm, 2003).

High water temperatures and high insolation have been found to be the primary proximate factors in mass bleaching events (Lesser, 2004; Hoegh-Guldberg, 1999). A number of researchers have used 1ºC, or a similar threshold, over the maximum value in a monthly long-term sea surface temperature (SST) climatology (sometimes referred to as the maximum monthly climatological mean) as a proxy for bleaching conditions (Hughes et al., 2003). These thresholds have been used successfully in several cases to predict both the onset of coral bleaching and overall bleaching intensity (Strong et al., 1997; Berkelmans et al., 2004).

The Northwestern Hawaiian Islands (NWHI), part of the Hawaiian Archipelago, stretch 1,200 nautical miles (2,200 km) northwest of the northernmost of the Main Hawaiian Islands (MHI) (Fig. 1). By Executive Orders in 2000 and 2001, the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve was designated, making the NWHI the second largest coral reef reserve in the world, second only to Australia's Great Barrier Reef Marine Park. The Islands are also unique in their extreme remoteness; the area is one of very few coral reef ecosystems largely free from significant fishing impacts and other local anthropogenic stressors. Several researchers have suggested further that the central Pacific location and high latitude of the Archipelago (Kure, the northernmost reef area, is centered at 28.5º N latitude) would make it one of the last places in the world to experience a massive bleaching event (Turgeon et al., 2002; Hoegh-Guldberg, 1999). These unique characteristics of the NWHI support the supposition that the NWHI provide important refugia for coral ecosystems from both localized anthropogenic stressors and degradation due to forecasted climate change.

Beginning in late July 2002, the U.S. National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch program identified elevated SST by both satellite and *in situ* observations near Midway in the NWHI. Based on these alerts, the focus of an annual interdisciplinary NOAA-led NWHI Reef Assessment and Monitoring Program expedition in September was modified to better investigate the predicted bleaching. Extensive data from these cruises were used to confirm that widespread massive coral bleaching had occurred, particularly at Kure, Midway, and Pearl and Hermes atolls at the northwestern end of the Hawaiian Archipelago (Aeby et al., 2003; Kenyon et al., in review).

In this paper, reasons for the gross distribution and severity of coral bleaching in the NWHI in 2002 are examined. Observed bleaching patterns are attributed to both large-scale regional oceanographic and meteorological conditions and to the local influences of reef and atoll morphology. Large differences between insular water temperatures and regional conditions have been noted in the Hawaiian Islands, especially during bleaching conditions (Jokiel and Brown, 2004). An empirical method of predicting overall differences in the amount of bleaching among reefs, based on lagoon and backreef containment volume, is discussed. For specific detail of the spatial and taxonomic distribution of bleaching severity, the reader is referred to Kenyon et al., in review.

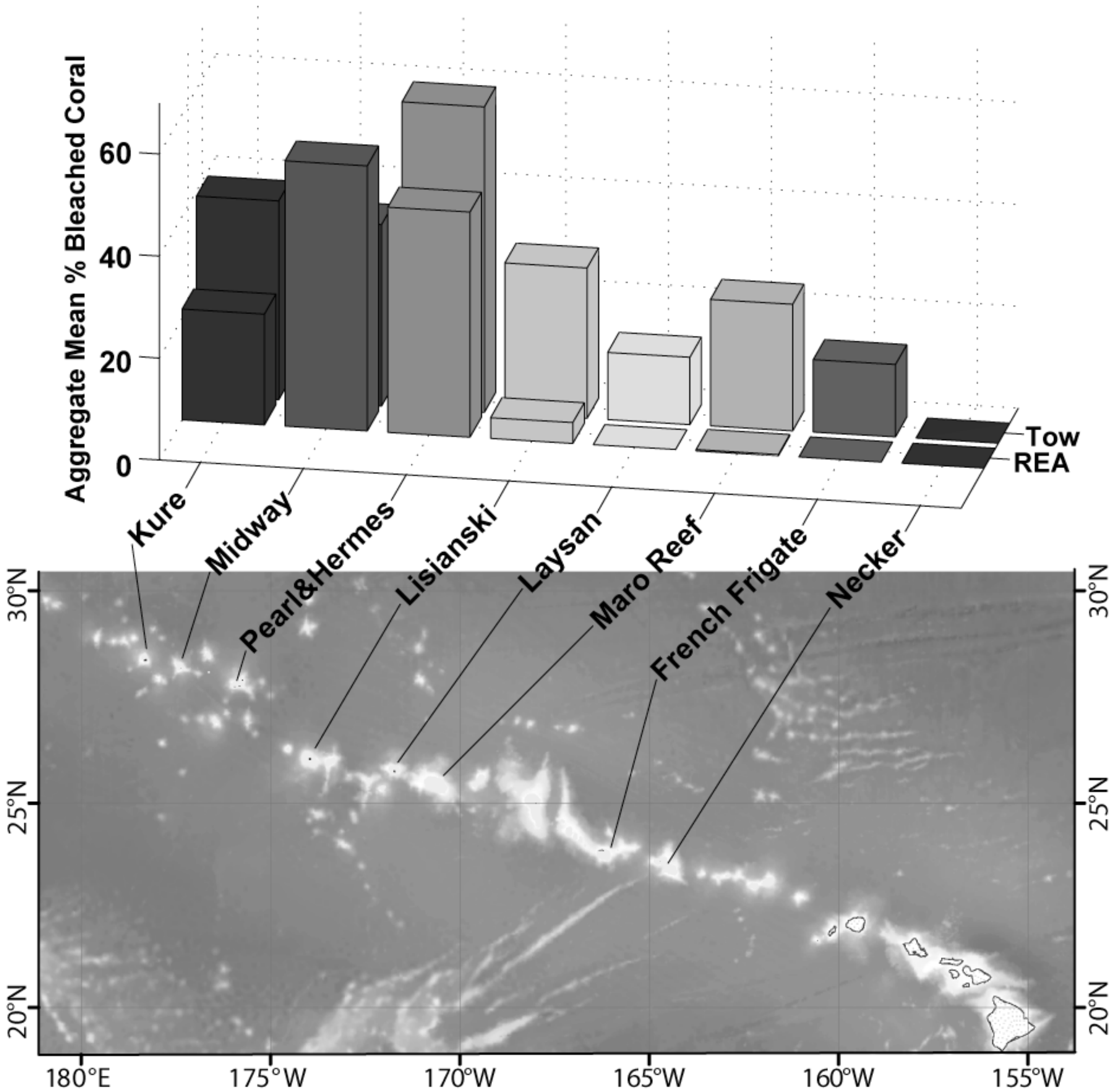

Figure 1. The Hawaiian Archipelago and gross distribution of coral bleaching observations from the 2002 Northwestern Hawaiian Islands mass bleaching event. Percent bleaching values presented in the bar graph above were generated by taking the mean observed percent bleached coral at all survey locations at each reef group location listed. Two survey techniques were used: rapid ecological assessments at fixed transects (REA) and towed-diver benthic survey video analysis (TOW). No bleaching was observed in the Main Hawaiian Islands in 2002.

METHODS

Three gridded data products were used to identify and describe the larger scale conditions implicated in the bleaching event. NOAA Pathfinder 9-km SST, a stable, well-documented satellite sea surface temperature data product (Vazquez et al., 2002) was used to establish a chronology of the elevated SST event and study overall SST distribution patterns. One degree latitude by one degree longitude location boxes were constructed around each island/reef group area in the Hawaiian Archipelago; the mean temperature for each spatial dataset was calculated for each location box to provide a time series. Maximum SST anomaly and degree heating weeks (DHW), a useful metric of heat exposures (Strong et al., 1997; Wellington et al., 2001), were calculated from this time series using the following equation:

$$\mathrm{DHW} = \sum \ [\mathrm{SSTA} > (\mathrm{Max.\ Monthly\ Mean})]$$

In other words, the value of DHW used here is simply the sum of SST Anomalies (SSTA) greater than the maximum monthly climatological mean SST for the particular location in question, over some time period, usually a year or less. For instance, 1 week of SST 1.5ºC above the maximum monthly climatological mean would result in a DHW value of 1.5.

NASA/JPL QuikSCAT SeaWinds, a satellite scatterometer surface level wind product (Piolle, 2002), was used to identify spatial and temporal correlations between wind patterns and SST. The same boxes defined for Pathfinder SST were used for the wind time series.

NOAA NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996) was used to qualitatively examine a number of surface variables, including: atmospheric pressure gradients, cloud cover, and incoming short-wave radiation levels.

The NOAA-led interdisciplinary Pacific Reef Assessment and Monitoring Program (Pacific RAMP) routinely collects *in situ* oceanographic data at the coral reef ecosystems in the U.S.-affiliated Pacific islands. These data include intensive sampling of temperature and salinity at different depths, performed concurrently with ecological assessments, as well as long-term temperature, salinity, current, wind, atmospheric pressure, and solar radiation measurements from instrument moorings (Brainard et al., 2004). Although intensive sampling of temperature and salinity was performed approximately 1 month after the end of the period of elevated SST, only data from instrument moorings was collected during the period of highly elevated regional SST indicated from the Pathfinder data. Temperature and salinity data from other time periods and other locations have been investigated to provide insights into small-scale circulation patterns during similar conditions. These data then were used to infer the existence of similar small-scale circulations and water properties in the NWHI during the 2002 event as have been observed elsewhere (see Results and Discussion section).

Estimates of coral bleaching used in this paper are derived from two methods of reef assessment utilized by NOAA Pacific RAMP: 1) Rapid Ecological Assessments (REA) belt transects, and 2) towed-diver benthic survey videos. Details of these methods are given in Kenyon et al.(in review). All quantitative bleaching estimates given in this paper are mean values for each of the assessment methods at each NWHI reef location (Fig. 1, Table 1).

Lagoon and backreef volumes were determined by digitizing the location of the reef crest at all NWHI reefs using IKONOS satellite imagery. The reef crest was identified generally as the interior limit of breakers visible in the imagery. This delimiter was easily defined in atoll morphologies such as French Frigate Shoals or Midway; areas of extremely complex morphology, such as Maro Reef or the Lisianski/Neva Shoals complex, sometimes required highly subjective estimations. Backreef/lagoon volumes

Table 1. Data summary table. REA and Towboard bleaching columns represent the mean fraction of bleached coral to total coral of all samples at each reef (after Kenyon et al., in review). SSTA and DHW represent the Pathfinder maximum SST anomalies and degree heating weeks, respectively. Area and volume columns represent lagoon and backreef planimetric areas and volumes derived from IKONOS satellite imagery.

	REA		Towboard					
	sites	**bleaching**	**tows**	**bleaching analysis**	**SSTA**	**DHW**	**Area**	**Volume**
Kure	9	0.217	11	0.390	1.967	7.13	4.61E+07	1.41E+08
Midway	9	0.520	15	0.356	1.603	6.89	6.65E+07	2.13E+08
Pearl& Hermes	14	0.442	22	0.599	1.496	5.87	3.60E+08	2.93E+09
Lisianski	7	0.041	10	0.295	0.752	2.85	5.06E+07	2.42E+08
Laysan	3	0.000	4	0.132	0.405	1.72	1.69E+06	3.60E+06
Maro	5	0.003	6	0.248	0.233	1.45	6.41E+07	6.11E+08
French Frigate	11	0.000	15	0.142	0.016	0.06	2.45E+08	1.91E+09
Necker	1	0.000	0	0.000	-0.112	0.00	1.60E+04	6.42E+04
Nihoa	-	-	-	-	-0.467	0.10	-	-
Kauai	-	-	-	-	0.168	0.78	-	-
Oahu	-	-	-	-	0.298	0.44	-	-

were then estimated by integrating depth values within the digitized reef crest; depths were calculated from IKONOS imagery using a method provided by Stumpf et al.(2003). Multiple regression analysis was used to establish relationships between DHW, lagoon and backreef volumes, and coral bleaching. A numerical algorithm was used to identify the relationship of the regression variables and associated coefficients.

RESULTS AND DISCUSSION

Large-Scale Regional Conditions

Reviewing the Pathfinder SST time series at selected locations, a rapid rise in sea surface temperatures followed by approximately 4 weeks of elevated temperatures is readily apparent at the northern end of the chain (Fig. 2). Pathfinder temperatures were well over 1 degree above the maximum monthly climatological mean at Midway, Kure, and Pearl and Hermes atolls during this event; temperatures of this magnitude often are associated with coral bleaching (Strong et al., 1997; Wellington et al., 2001). Reef groups towards the southeast experienced progressively smaller positive temperature anomalies and DHWs with distance from these northern atolls (Fig. 2). The spatial extent of this high temperature anomaly can be seen as a broad band across the northern end of the Hawaiian Archipelago, while the Main Hawaiian Islands experienced near normal or even slightly cooler than normal surface water temperatures (Fig. 3a).

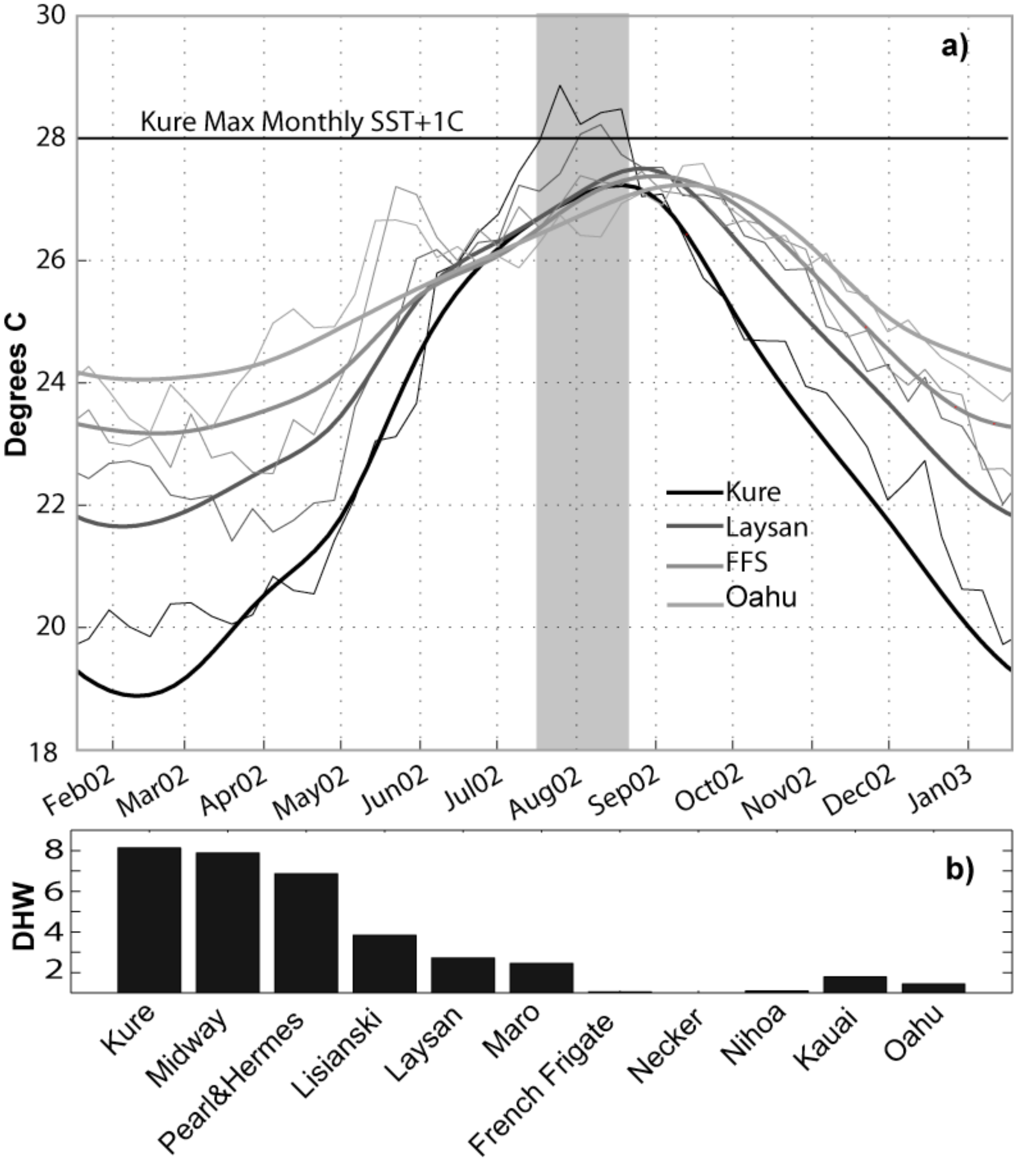

Figure 2. a) NOAA Pathfinder SST time series at four locations in the Hawaiian Island Chain centered on the summer of 2002. The thicker smooth lines represent interpolated monthly climatological Pathfinder SST; the finer lines represent the 2002 time series; both were constructed from 1ºx1º boxes surrounding each region above. The approximately four-week period of highly elevated Pathfinder SST (July 28 – August 29) is highlighted with a grey bar in the center of the plot. b) Degree Heating Weeks (DHW) for 2002 constructed from the same 1ºx1º boxes.

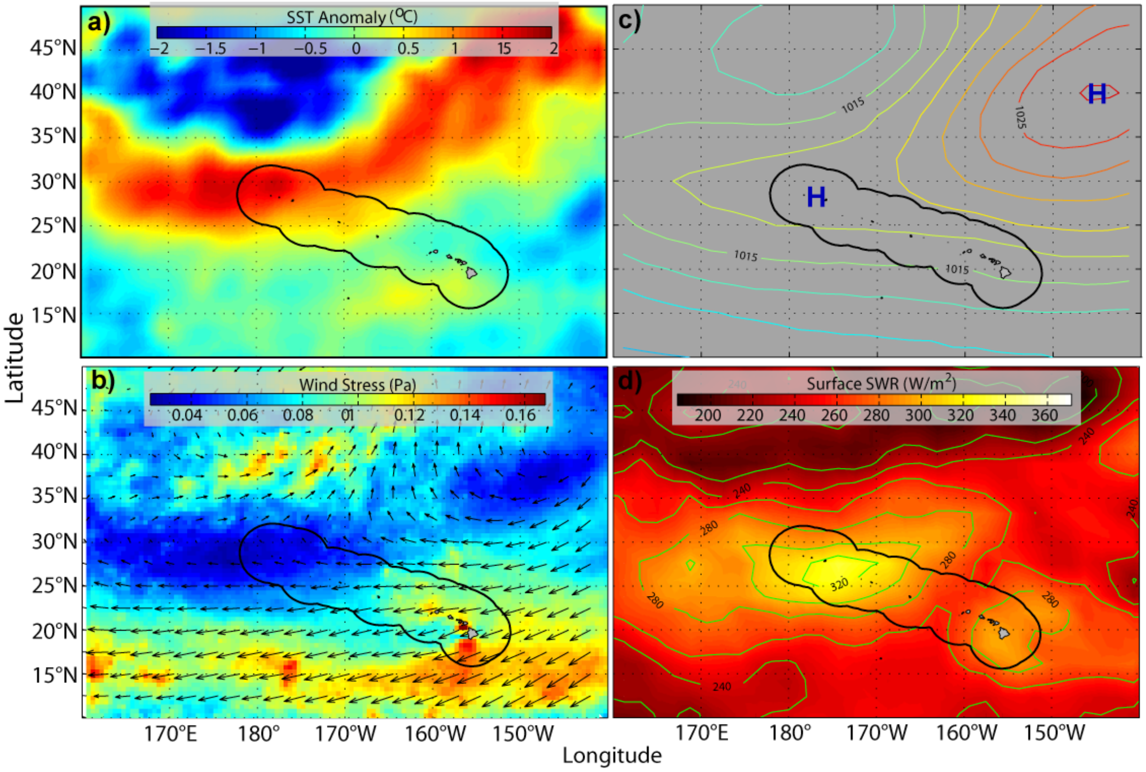

Figure 3. a) NOAA Pathfinder SST anomaly composite during summer 2002 period of NWHI elevated temperatures, July 28 – August 29. b) NASA/JPL Quikscat winds (wind stress overlayed by wind vector arrows) composite during summer 2002 period of increasing SSTs, July 16 – August 13. c) Mean NCEP Sea Level Pressure Reanalysis, July 16 – August 16. d) Mean NCEP Surface Short Wave Radiation Reanalysis, July 16 – August 16. In each graphic above, the Hawai'i Exclusive Economic Zone (EEZ) is indicated with a heavy black line; all island shorelines in the archipelago are also plotted.

The distribution of high temperatures appears to be linked directly to exceptionally quiescent winds preceding and during the event; good correspondence exists between low wind speeds and rapid increase in SST during this period (Fig. 3b). In turn, these light winds were linked with a variable, but persistent high-pressure ridge associated with the North Pacific Subtropical High (Fig. 3c). The axis of the ridge generally intersected the northern end of the Hawaiian Archipelago for much of the summer, coinciding with the light winds, very low cloud cover, and high surface insolation (Fig. 3d). In the MHI, by contrast, wind speeds remained consistently much higher, with trade winds driven by the atmospheric pressure gradient south of the high-pressure ridge.

Small-Scale Morphological Effects

While synoptic weather features describe the gross distribution of both SST and observed bleaching at the archipelago scale, they do not explain relatively large differences in the overall extent and severity of bleaching observed among adjacent reef groups. These differences are most evident at Laysan Island, where significantly less overall bleaching was recorded than at neighboring Maro Reef or Lisianski/Neva Shoals (Kenyon et al. in review). Less overall bleaching also was documented at Kure Atoll than at neighboring Midway Atoll, despite Kure experiencing slightly higher Pathfinder SSTs. While these differences are partially due to differences in coral species compositions and distributions at the different locations (Kenyon et al., in review), they are likely also due in large part to differences in water circulation connected to differing reef morphologies.

During a Pacific RAMP assessment at Rose Atoll in American Samoa, researchers documented the formation of a lens of highly stratified water within the atoll's lagoon and inner reef flat that was up to 3ºC warmer than surrounding water temperatures (Hoeke, 2002, unpublished data). The meteorological conditions during this visit (light winds and high atmospheric surface pressure) were similar to those of the NWHI 2002 bleaching event. The formation of such a warm water lens can be attributed to surface gravity wave setup across the forereef, which mechanically mixes water over the forereef, but causes surface convergence within the lagoon and backreef (Krains et al., 1998; Prager, 1991). In light wind conditions, wave setup across the forereef would tend to balance baroclinic forcing (horizontal density gradients), heating surface waters trapped within the atoll throughout the day, with little or no mixing (Andrews et al., 1984).

In situ measurements of SST support the supposition that similar features occurred within the northern atolls in the NWHI at the time of bleaching in 2002. During the warming period preceding the bleaching event, average *in situ* SST measured near the center of Pearl and Hermes' lagoon was 0.7ºC warmer than Pathfinder SST of the surrounding area, and diurnal maxima were up to 2.6ºC warmer (Fig. 4).

Local water circulations are highly dependent on reef morphology (Atkinson et al., 1981). Atolls, with narrow forereefs and large protected lagoons, likely are prone to these lens-like stratified features during low wind conditions, while it is unlikely that such features occur at islands with fringing reef systems. The residence time of water in lagoon and backreef areas is related to water volume (Delesalle and Sournia, 1992), and therefore might serve as one of the primary factors controlling the extent and temperature maxima of these features in the Northwestern Hawaiian Islands, where tidal mixing is low compared to gravity wave mixing at shallow reef depths (Andrews et al., 1984; Atkinson et al., 1981). These hypotheses explain why Laysan Island, with its fringing reef and very little backreef area, experienced less overall coral bleaching than neighboring reefs on either side, and why Pearl and Hermes Atoll, with its complex, large, deep lagoon and narrow encircling forereef, experienced the most. Lisianski Island and its associated Neva Shoals complex of both fringing reef and backreef areas may represent an intermediate case (Fig. 1, Table 1).

Kenyon et al. (in review) describe significant differences in overall bleaching within the atolls' different morphological zones and inverse correlation of bleaching severity with depth. Bleaching was greatest within shallow backreef and lagoon areas, and least on the forereefs. These observations are consistent with the inference that highly stratified waters with surface layers significantly warmer than surrounding open ocean conditions occurred in lagoon and backreef areas, while forereef areas remained relatively cool as turbulence due to surface gravity waves rapidly mixed surface layers heated by daytime insolation.

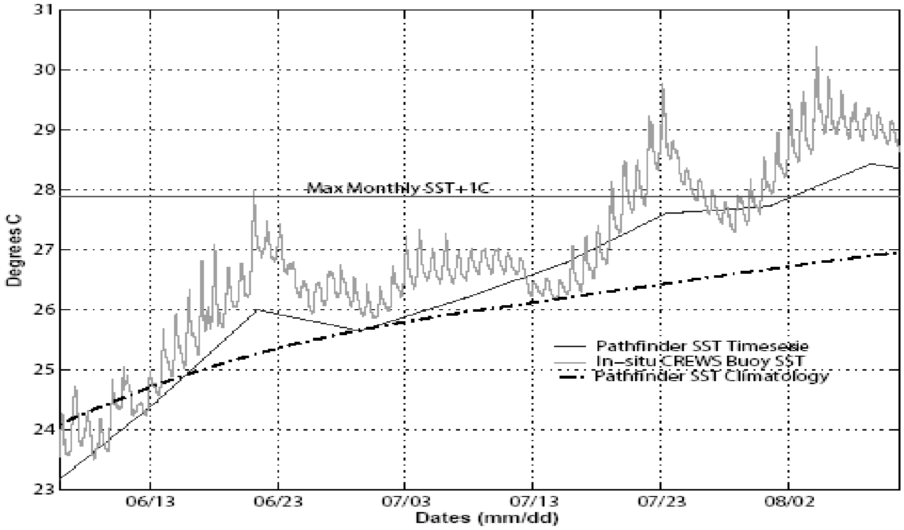

Figure 4. Comparison of Pathfinder SST in the area of Pearl and Hermes Atoll and in situ water temperatures measured near the center of the Atoll at a depth of approximately 1 m. Maximum departure of in situ temperatures from Pathfinder SST is +2.6ºC.

Prediction of Differences in Bleaching Among Adjacent Reefs

Several researchers have developed indices of bleaching severity using DHWs (Strong et al., 1997; Wellington et al., 2001), such as those provided by NOAA’s Oceanic Research and Applications Division (ORAD) products. Regression of DHW alone describes between 60-80% of the variability seen in overall mean coral bleaching observations among reefs (Fig. 5, Table 2). As outlined above, such satellite SST-derived products help describe and predict gross, archipelago-scale bleaching, but cannot account for differences among adjacent reefs due to local circulation patterns and mixing. These

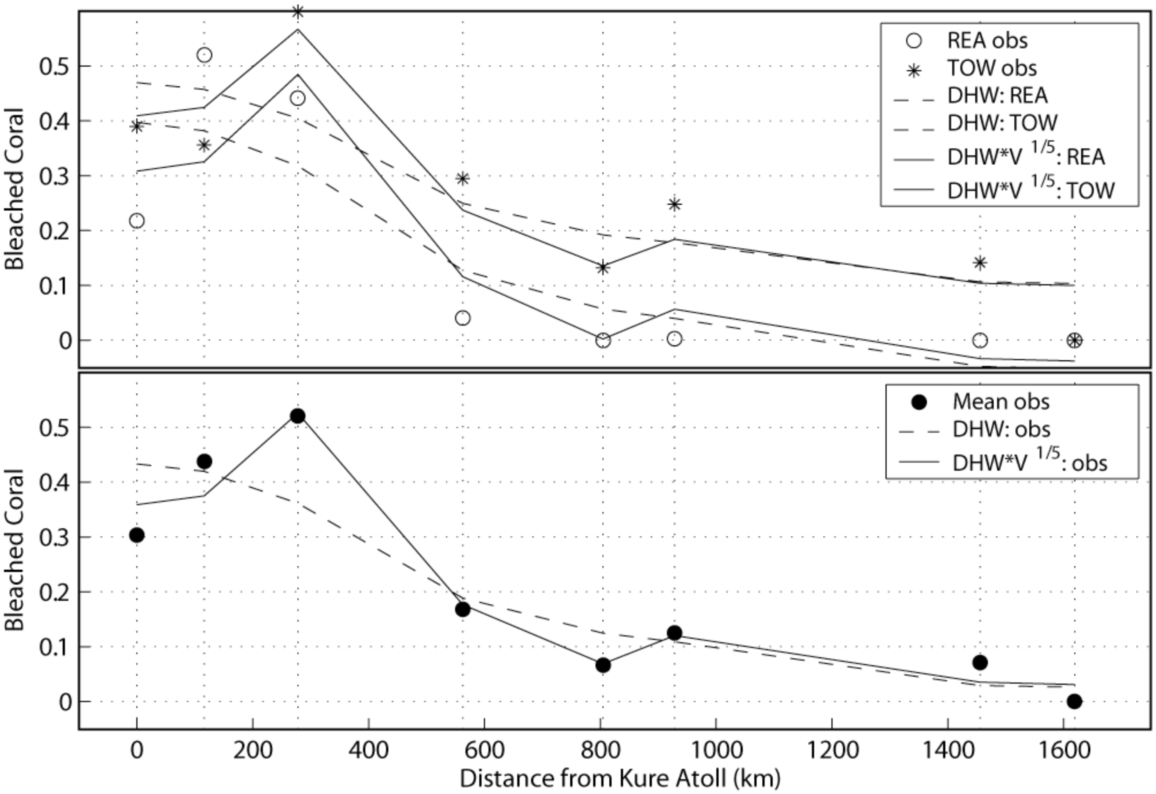

Figure 5. Comparison of mean bleaching variance described by DHW versus DHW·$V^{1/5}$ at NWHI locations. REA obs and TOW obs in the upper panel indicate observations from the rapid ecological assessments at fixed transects and towed-diver benthic survey video analysis, respectively; Obs in the lower panel represents mean of all observations of all methods at each location. Predictions based on regression of DHW are given with dashed lines. Predictions based on regression of DHW and fifth root of lagoon and backreef volume ($V^{1/5}$) are given with solid lines.

Table 2. Variance, F-, and p-statistics for the regression analysis of mean bleaching observations for each reef in the NWHI from Necker to Kure. REA and TOW indicate observations from the rapid ecological assessments at fixed transects and towed-diver benthic survey video analysis, respectively; mean represents mean of all observations of all methods at each location. The upper portion is regression statistics using DHW alone; the lower is multiple regression of DHW and the fifth root of lagoon and backreef volume, as explained in the text.

Degree Heating Weeks (DHW)

	r^2	F	p
REA	0.7443	17.4643	0.0058
TOW	0.6791	12.6996	0.0119
Mean	0.80431	24.6612	0.0025

DHW·$V^{1/5}$

	r^2	F	p
REA	0.8195	27.2407	0.0020
TOW	0.8959	51.6156	0.0004
Mean	0.9624	153.894	0.0000

differences are reflected in the local heat budgets of the adjacent reefs as changes to the advective heat flux and turbulent diffusive (mixing) heat flux terms (Dong and Kelly, 2003). Temperature changes for reservoirs and estuaries often are estimated using bulk formulations (Beck et al., 2001; Fischer et al., 1979). If lagoons and backreefs are considered a reservoir, than changes in temperature can be estimated by the following bulk formula:

$$\frac{dT}{dt} = \underbrace{\frac{Q_{net}}{C_p \rho V}}_{1} - \underbrace{\frac{(U_{in} T_{ocean} - U_{out} T_{lagoon})}{V}}_{2}$$

In term 1, on the right side of the equation, Q_{net} is the total net heat flux through the air-sea interface of the lagoon and backreef surface area; C_p is the specific heat of the water; and ρ is the density of the water. Term 2 represents a bulk estimation of heat advection and mixing between the ocean and the lagoon: U_{in} and U_{out} are the total volume flux of the water coming into and out of the lagoon/backreef; T_{ocean} and T_{lagoon} represent the temperature of the surrounding oceanic water and the mean temperature of the lagoon. In both terms, V is the volume of the lagoon/backreef reservoir. Thus, for neighboring reefs experiencing similar meteorological conditions, it is primarily the ratio of total volume flux to V that defines differences in temperature among reefs. Residence time is defined as $R=V/U_{total}$ (Delesalle and Sournia, 1992), where U_{total} is the total volume flux of the lagoon/backreef. Reefs with longer lagoon/backreef residence times exchange less heat per unit volume with the relatively cooler forereefs and open ocean.

Unfortunately, accurate estimation of the total volume flux (U_{total}) is extremely difficult, and generally requires intensive measurements and/or complex numerical modeling. It is possible, however, that volume flux is linked to volume, especially in areas with similarities in small-scale morphological features. If volume flux per unit width across the forereef barrier is the same among reefs, then volume flux will increase in a nonlinear fashion with volume for basins with roughly the same geometry. Based on this assumption, regression analysis of bleaching to DHW multiplied by the additional factor of the volume to a constant power was investigated, e.g.:

$$Bleaching = a \cdot DHW \cdot V^k + b$$

where *a*, *b*, and *k* are regression constants. In this case, the best-fit value of the nonlinear coefficient, *k*, was 1.5. This method, while relying on admittedly tenuous assumptions, describes approximately 80-90% of the variability of the observed coral bleaching, and represents a statistically significant improvement over the relationship to DHW alone (Table 2). Figure 5 shows the ability of the empirical relationship to account for large differences in observed overall bleaching among adjacent reefs not accounted for by SST anomaly or DHW alone. This suggests that such empirical relationships between DHW and lagoon/backreef volumes are potentially useful to better describe heat stress to corals.

CONCLUSIONS

High water temperatures and high ultraviolet (UV) radiation have been identified as the primary stressors leading to coral bleaching (Hoegh-Guldberg, 1999). Although UV radiation probably played a large role in bleaching severity during the 2002 NWHI event, as observations of greater bleaching on the upper surfaces of individual coral colonies suggest (Kenyon et al., in review), overall spatial patterns of bleaching can be described by measured and inferred distributions of water temperatures alone. SST anomalies associated with archipelago-scale bleaching patterns appear to be directly connected to a series of atmospheric high-pressure ridges present shortly before and during the onset of elevated temperatures. These atmospheric features, extensions of the North Pacific Subtropical High, were centered over the northwestern end of the Island chain, where the greatest SST anomalies occurred. In contrast, atmospheric pressure gradients to the southeast maintained trade winds, mixing the surface layer and keeping SSTs relatively cooler. Circulation patterns influenced by reef morphology coupled with light winds further elevated water temperatures (up to 3°C) at some locations, particularly at the three northernmost atolls: Kure, Midway, and Pearl and Hermes.

Based on the ~20 year Pathfinder dataset, SSTs at the northwestern end of the Hawaiian chain reached higher temperatures and remained elevated (>1°C over climatological means) for longer than any other warming episodes in the entire Archipelago. Although gross patterns of SST anomaly associated with the bleaching event are linkable to synoptic weather patterns near the time of the event, the magnitude of the anomaly is probably at least partially due to longer-term processes. While SST anomalies at the northern end of the Hawaiian Archipelago were not significant during the springtime preceding the summer of 2002, wintertime SSTs over the 3 years preceding the event have been noticeably elevated (~>1°C) over climatological means. Higher wintertime SSTs over several years point to large-scale climate oscillations such as the Pacific Decadal Oscillation (PDO) (Schneider et al., 2002). It is also of note that all episodes of elevated SST in the NWHI occurred during periods of a positive El Nino/ Southern Oscillation phase (ENSO), although the magnitude of SST anomaly does not correspond with the magnitude of ENSO. It is beyond the scope of this work to identify links between large-scale climate oscillations and bleaching conditions, but they appear to play a major role.

Mean summertime SST (June 15 – September 15) maxima (based on Pathfinder data) are 0.4°C warmer at Midway than at Oahu, and summertime SSTs have higher standard deviation toward the northern end of the chain. The higher variability and higher maximum temperatures suggest that more frequent episodes of high surface water temperatures coupled with light and variable winds, conditions associated with mass bleaching, occur at the northwestern end of the Hawaiian Archipelago than in the MHI; although notable exceptions occur such as a bleaching event in the MHI in 1996 (Jokiel and Brown, 2004). These temperature characteristics, along with the hypothesized circulation patterns of atolls in low wind conditions, strongly suggest that the northern atolls of Kure, Midway, and especially Pearl and Hermes are at the greatest risk of future mass bleaching episodes of all reef ecosystems within the Hawaiian Archipelago.

Based on the NWHI 2002 bleaching observations, the overall bleaching a particular reef experiences appears to be well parameterized by an empirical relationship to satellite-derived heat exposure (DHW) and the lagoon/backreef volume. Although local flushing and mixing in the NWHI's reefs are very complex and largely unknown, using a nonlinear factor of the lagoon/backreef volumes appears to capture the effect of localized heating in a statistically significant fashion (Table 2). Until these circulations are better understood, which probably requires fine-scale hydrodynamic modeling, the propensity of a particular reef to experience bleaching may be described from this simple relationship. Pearl and Hermes Atoll, with its vast lagoon and backreef area, would have the highest likelihood of experiencing the greatest amount of coral bleaching. It is unlikely that a similar relationship exists for the MHI, where freshwater input, turbidity, and other orographic effects associated with high islands have been shown to influence bleaching patterns (Jokiel and Brown, 2004). More investigation into relationships among local heat stress, residence times, and reef morphology is warranted.

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