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Overview of NOAA Coral Reef Watch Program's Near-Real-Time Satellite Global Coral Bleaching Monitoring Activities

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Abstract Coral bleaching has been considered as one of the major contributors to the increased worldwide deterioration of coral reef ecosystems being reported over the past few decades. Understandably the need for improved understanding, monitoring, and prediction of coral bleaching becomes imperative. Satellite remote sensing has become a key tool for coral reef managers and scientists, providing the capability of synoptic views of the global oceans in near-real-time and the ability to monitor remote reef areas. As early as 1997, NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) began producing near-real-time, web-accessible, satellite-derived sea surface temperature (SST) products to monitor conditions conducive to coral bleaching from thermal stress around the globe. In 2000, this activity enabled the genesis of NOAA's Coral Reef Watch (CRW) Program. Over the past couple of years, most of its key products, including SST anomalies, bleaching HotSpots, Degree Heating Weeks (DHW), and Tropical Ocean Coral Bleaching Indices webpage became "operational" products after successfully providing early warnings of coral bleaching to the U.S. and global coral reef communities as "experimental" products for several years. Currently, several new near-real-time products, including Short-Term Trends of Thermal Stress, Duration of Thermal Stress, Number of Stress Days, and an automated e-mail alerting system, are in the final stages of development and should become available soon. As we attempt to improve the accuracy of the monitoring products and develop prediction capabilities, CRW is seeking to develop these products at higher spatial resolutions, monitor other related environmental parameters (such as surface wind, solar radiation, and wave field), incorporate numerical model simulations, and develop new and more accurate algorithms. CRW's mission is to provide the domestic and international coral reef communities with timely and accurate information for understanding, monitoring, and preserving these "rainforests of the sea."

Keywords coral, bleaching, satellite remote sensing, sea surface temperature, HotSpot, Degree Heating Week, monitoring

Introduction

Coral reefs are the most diverse and complex marine ecosystem and comprise the largest biological structure on the earth. Well-developed coral reefs reflect thousands of years of history. Recently, however, coral reefs have been facing increasing hazards and threats and many coral habitats worldwide have been declining rapidly (e.g., Glynn, 1996).

Most reef-forming corals contain symbiotic microscopic algae within their gastrodermal cells (Yonge and Nicholls, 1931). Healthy corals come in a variety of colors, depending on the photosynthetic pigments of their symbiotic algae. However, under certain environmental stresses, the algae can be expelled by the host corals. Lacking their symbiotic algae, the corals reveal their white underlying calcium carbonate skeleton through the translucent coral tissue and the affected coral colony becomes stark white or pale in color. This phenomenon is commonly known as "coral bleaching" (Berkelmans and Willis, 1999; Reaser et al., 2000).

Coral bleaching is often caused by ambient water temperatures that exceed the coral's tolerance level (e.g., Glynn and D'Croz, 1990; Lesser et al., 1990). This may be as little as 1 to 2^{o}C above the mean monthly summer values (Coles and Jokiel, 1977; Jokiel and Coles, 1990). High temperature not only contributes to bleaching but also reduces coral's normal growth and reproductive capacity (Szmant and Gassman, 1990; Ward et al., 1998; Hoegh-Guldberg, 1999). Bleaching may also weaken coral's ability to fight disease (Cervino et al., 1998; Richardson et al., 1998). Prolonged thermal stress over bleached corals often leads to the death of the corals (e.g., Hoegh-Guldberg, 1999; Wilkinson et al., 1999). Severe bleaching events have dramatic long-term ecological impacts, including loss of reef-building corals, changes in benthic habitat, and, in some cases, changes in fish population (Munro, 1996; Berkelmans and Oliver, 1999; Done, 1999). Even under favorable conditions, it can take many years for severely bleached reefs to recover (Hughes, 1994; Connell et al., 1997; Done, 1999).

Bleaching may occur at local scales or at geographic scales. A mass bleaching event is a bleaching event occurring at geographic scales that may involve entire reef systems and geographic realms (Hoegh-Guldberg, 1999). Mass bleaching events occur much less frequently than local scale bleaching events which are often caused by local environmental factors.

Climate change is considered to be one of the greatest threats to the world's coral reefs over the next few decades and may be somewhat responsible for large-scale deterioration over the past few decades (Hughes et al., 2003). Anomalously high sea surface temperatures (SSTs) driven by natural climate events (e.g., 1997-1998 El Niño) occurring in association with rising sea temperatures have caused large-scale mass coral bleaching over the past few decades (i.e., Montgomery and Strong, 1994; Hoegh-Guldberg, 1999; Goreau et al., 2000; Wellington et al., 2001; Strong et al., 2002; Liu et al., 2003). These changes have resulted in the loss of reef-building corals on an unprecedented scale across large areas of the world's tropical oceans (Glynn, 1996; Hoegh-Guldberg, 1999; Wilkinson, 1999).

Coral reef areas are being monitored more extensively now than ever for environmental conditions associated with bleaching. As early as 1997, the U.S. National Oceanic and Atmospheric Administration (NOAA)'s National Environmental Satellite, Data, and Information Service (NESDIS) began to provide near-real-time satellite remotely-sensed SSTs and extended information, derived from SSTs, to the U.S. and global coral reef communities as a means of detecting and monitoring thermal stress conducive to bleaching. The NESDIS satellite monitoring activity is now a core component of NOAA's Coral Reef Watch (CRW) Program. An overview of the current near-real-time global satellite coral bleaching monitoring activities at NOAA's CRW is given in this paper.

Development of the CRW near-real-time satellite coral bleaching monitoring activities

Following several years of research projects in collaboration with midshipmen from the U.S. Naval Academy (e.g., Montgomery and Strong, 1994; Gleeson and Strong, 1995), the world's first near-real-time satellite global bleaching monitoring system was developed in 1996 at NOAA/NESDIS (Strong et al., 1997). The near-real-time monitoring system was inaugurated in 1997, providing web-accessible products to both the U.S. and global coral reef communities. In 1997, the system included only one monitoring tool, bleaching HotSpots (see the next section for the description). By 2000, a suite of satellite global coral bleaching monitoring tools had been developed at NESDIS, including bleaching Degree Heating Weeks (DHW, see the next section for the description). This satellite bleaching monitoring system has been and still is the only system of its kind available in the world and possibly represents the only global suite of operational satellite products currently being used for the management of any marine ecosystem (Skirving et al., 2005).

NOAA's CRW (http://coralreefwatch.noaa.gov/) was established in 2000 with NESDIS' satellite bleaching monitoring system serving as a core component. NOAA's CRW, established to provide early warnings and long-term monitoring for both U.S. and global coral reef ecosystems, is mainly a monitoring program that includes both satellite and *in-situ* monitoring components. Most of the *in-situ* monitoring in CRW is conducted by NOAA's Office of Oceanic and Atmospheric Research (OAR), National Marine Fisheries Service (NMFS), and National Ocean Service (NOS). In early 2004, the NOAA Coral Reef Ecosystem Integrated Observing System (CREIOS) was established to integrate NOAA's monitoring, mapping, and observing of coral reef ecosystems by NESDIS, NMFS, OAR, and NOS.

Suite of CRW near-real-time satellite global coral bleaching monitoring tools

Currently, the primary CRW near-real-time satellite global coral bleaching monitoring tools include the operational near-real-time satellite global 50-km nighttime SSTs, coral bleaching HotSpots, coral bleaching DHWs, Tropical Ocean Coral Bleaching Indices webpage, and SST time series for selected reef sites (Fig. 1). Most of these primary products are presented in graphic format and posted online for easy global access. Animations of SST, HotSpot, and DHW charts over the most recent 2, 4, and 6 months are also produced and posted on the web. These products were developed based on earlier work by Montgomery and Strong (1994), Gleeson and Strong (1995), Strong et al. (1997), and Goreau et al. (2000).

The coral bleaching HotSpot (Fig. 1a) is a type of SST anomaly giving the difference between a nighttime SST value (Fig. 1b) at a given time at a given location and the corresponding climatology value for the same location (Strong et al., 1997; Liu et al., 2003; Skirving et al., 2005). The climatology currently used for deriving the bleaching HotSpot is the climatological mean temperature of the climatologically warmest month at the location. It is often referred to as the maximum of the monthly mean SST climatology, otherwise known as MMM climatology. This climatology, derived from the Polar-orbiting Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR) nighttime SSTs for the period 1985-1993, is static in time for any given location, but varies geographically. This satellite coral bleaching HotSpot product was developed at NOAA/NESDIS in 1996 based on the "ocean hot spots" concept introduced by Goreau and Hayes (1994). From 1997, HotSpot was produced

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routinely as an experimental product to measure the occurrence and intensity of anomalously high SSTs (Strong et al., 1997) and became the first operational product in September 2002. Pinpointing the location of thermal stress conducive to coral bleaching in the global tropical oceans, HotSpot charts display only positive values of this specialized anomaly.

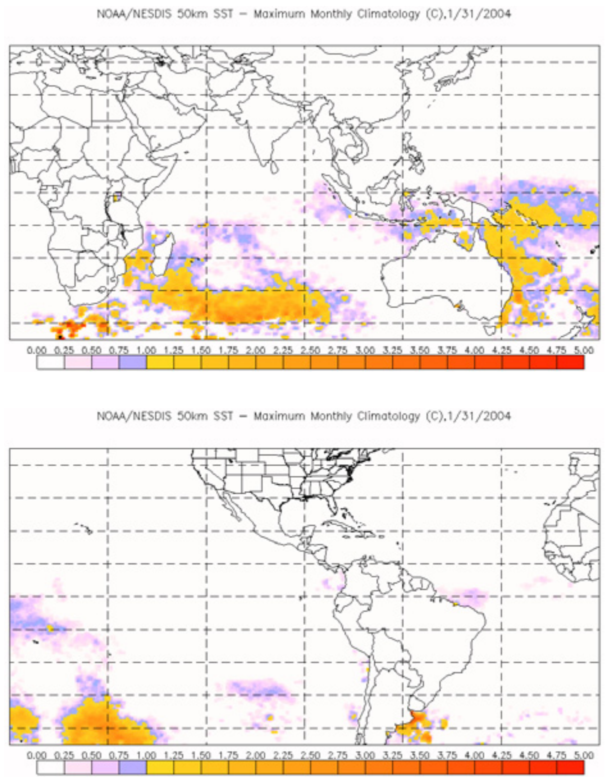

Fig. 1a. CRW's operational twice-weekly near-real-time satellite 50-km coral bleaching HotSpot charts of January 31, 2004 for the Eastern Hemisphere (upper chart) and Western Hemisphere (lower chart).

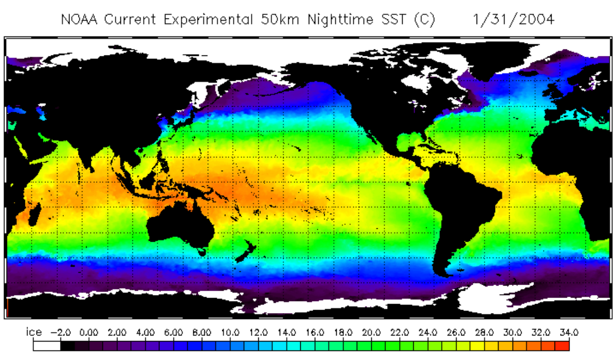

Fig. 1b. CRW's operational twice-weekly near-real-time satellite global 50-km nighttime SST chart of January 31, 2004.

To measure the cumulative extent of thermal stress experienced by coral reefs, a thermal stress index, called a DHW (Fig. 1c), was also developed at NOAA/NESDIS (Strong et al., 1997). It became available experimentally for near-real-time monitoring at the beginning of 2000 and became an operational product in September 2003. DHW for a given location represents the accumulation of HotSpots at that location over a rolling 12-week time period (Liu et al., 2003; Skirving et al., 2005). Preliminary indications show that typically a HotSpot value of less than one degree Celsius is insufficient to cause visible stress on corals. Consequently, only HotSpot values ≥1°C are accumulated (i.e., if there are consecutive weekly HotSpot values of 1.0, 2.0, 0.8, and 1.2°C, the DHW value will be 4.2 because 0.8 is less than one and, therefore, does not get accumulated). One DHW is equivalent to one week of HotSpot levels staying at 1°C or half a week of HotSpot levels at 2°C, and so forth.

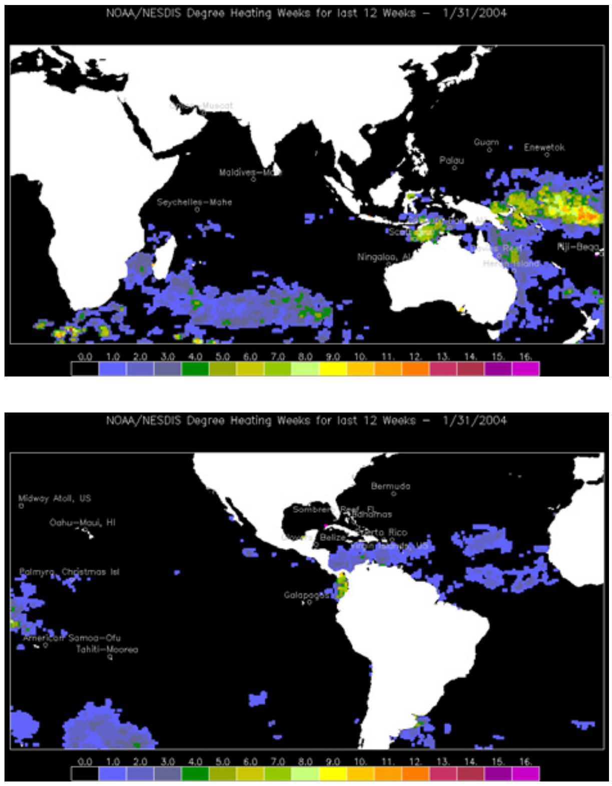

Fig. 1c. CRW's operational twice-weekly near-real-time satellite 50-km coral bleaching DHW charts of January 31, 2004 for the Eastern Hemisphere (upper chart) and Western Hemisphere (lower chart).

Field observations (most of which are subjective measurements presented as informal reports) with coincident satellite data are only available for a limited number of years, but do include the 1998 worldwide mass bleaching events. Collectively, these observations indicate that there is a correlation between bleached corals and DHW values of four or greater (Liu et al., 2003; Skirving et al., 2005). When DHW values reach eight, widespread bleaching is likely and some mortality can be expected. CRW has applied these DHW levels when generating satellite bleaching warnings and alerts (Wellington et al., 2001; Liu et al., 2003). These products have been successful in monitoring major coral bleaching episodes around the globe since 1997 (e.g., Wilkinson et al., 1999; Goreau et al., 2000; Wellington et al., 2001).

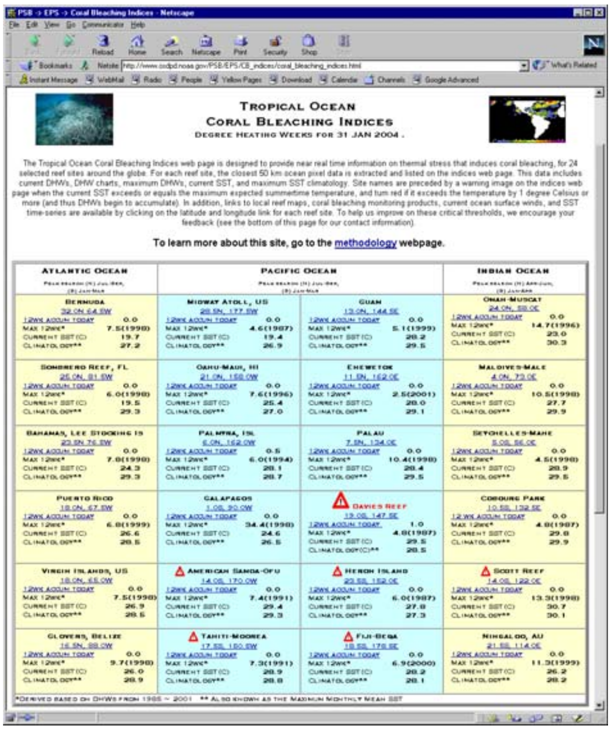

Fig. 1d. CRW's operational twice-weekly near-real-time satellite Tropical Ocean Coral Bleaching Indices webpage of January 31, 2004, for 24 selected reef sites around the globe.

CRW's satellite Tropical Ocean Bleaching Indices webpage (Fig. 1d) provides actual numerical values of near-real-time SST and DHW, along with the MMM climatology values, currently for 24 selected reef sites around the globe. Numerical values typically offer more accurate information than the information extracted from graphic displays using color scales; whereas, the chart overview provides extent and often shows connectivity with adjacent reef systems. A small red triangular warning sign (Fig. 1d) appears next to a reef name when the SST at a representative satellite pixel closest to the reef exceeds the MMM climatology value at the pixel; whereas, a large red triangular warning sign appears next to the reef name and the name is colored red when a DHW value has accumulated during the past twice-weekly time period. Among the 24 sites, six are in the Atlantic Ocean (Bermuda, Sombrero Reef, Lee Stocking Island, Puerto Rico, US Virgin Islands, and Glover's Reef Atoll); twelve in the Pacific Ocean (Midway Atoll, Oahu-Maui, Palmyra Island, Galapagos, American Samoa, Tahiti-Moorea, Guam, Enewetok, Palau, Davies Reef, Heron Island, and Fiji-Beqa); and six in the Indian Ocean (Oman-Muscat, Maldives-Male, Seychelles-Mahe, Cobourg Park, Scott Reef, and Ningaloo Reef). The page also provides numerous links to the corresponding regional reef maps and satellite near-real-time wind fields.

CRW's satellite temperature time series webpage is the entry point to the time series charts (Fig. 1e) of these 24 selected reef sites. These time series go back to 1985. Animations of SST, HotSpot, and DHW charts over the most recent 2-, 4-, and 6-month time periods (not shown) are produced and posted online for easy monitoring of the temporal development and spatial evolution of thermal stress.

All of these near-real-time CRW products are presently being updated twice-a-week in near-real-time using the updated NOAA/NESDIS operational twice-weekly composite satellite nighttime AVHRR SST field. On Tuesdays, the twice-weekly satellite composite SST data, derived from daily SST retrievals obtained from the previous Saturday through Monday, are used for updating bleaching products and, similarly, on Saturdays, data from the previous Tuesday through Friday are used. These near-real-time products, along with the descriptions of methodologies, are web-accessible at http://coralreefwatch.noaa.gov/satellite. All the static twice-weekly data and charts are archived and also web-accessible at the above website. The animations are not archived.

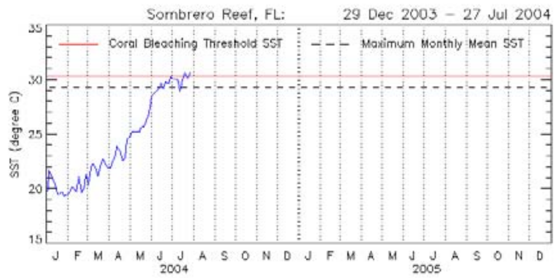

Fig. 1e. CRW's operational twice-weekly near-real-time satellite SST time series chart as of July 27, 2004, for a representative pixel closest to Sombrero Reef, Florida. The static MMM climatology value (black dashed line) and MMM+1ºC (red line) at the pixel are also plotted.

Application of the CRW satellite coral bleaching monitoring tools: a demonstration

In this section, a mass coral bleaching event is used as a sample to demonstrate how the CRW near-real-time monitoring tools are applied for detecting the occurrence and monitoring the development of thermal stress responsible for a bleaching event.

During the summer of 2002, a mass coral bleaching was observed in the Northwestern Hawaiian Islands (NWHI). This bleaching event was reported as the first mass bleaching event ever observed in this remote and relatively pristine large-scale coral reef ecosystem (Aeby et al., 2003). A series of CRW near-real-time, twice-weekly, HotSpot charts (Fig. 2) shows the development of the thermal stress in the North Pacific Ocean at several stages during the summer of 2002. These HotSpot charts were modified from the original near-real-time global HotSpot charts to show only the North Pacific Ocean. The original near-real-time, twice-weekly, HotSpot charts are archived and web-accessible at

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http://www.osdpd.noaa.gov/PSB/EPS/SST/climohot_2002.html. Near-real-time animations of HotSpots charts were also used at the time for monitoring the evolving development of the thermal stress across the region. The little cross on the charts in Fig. 2 marks the location of Midway Atoll of the NWHI, which is near the northwest end of the NWHI. In the NWHI region, the thermal stress, shown by positive HotSpots, first appeared in late July, reached its maximum strength in early August, achieved its maximum spatial coverage in the NWHI in late August, and disappeared from the region by late September. The accumulation of DHW in the NWHI lasted over 10 weeks. The thermal stress first developed in the region west-northwest of the NWHI and then expanded east-southeastward into the NWHI. The intensity of the HotSpot decreased as the thermal stress evolved towards the southeast.

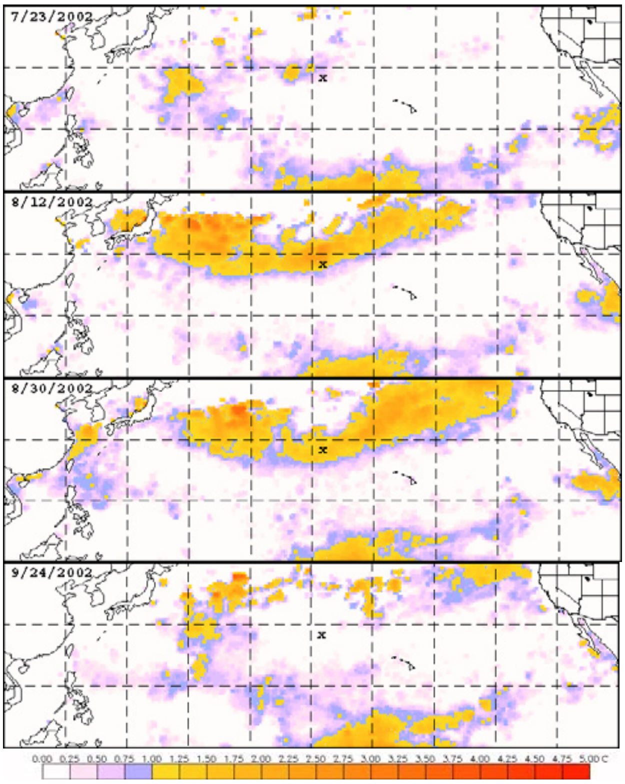

Fig. 2. CRW's near-real-time HotSpot charts of July 23, August 12, 30, and September 24, 2002, showing the development of thermal stress in the North Pacific Ocean. The little cross on the charts marks the location of Midway Atoll of the NWHI, which is near the northwest end of the NWHI. The islands shown to the far southeast of the Midway Atoll are the Main Hawaiian Islands, which are off the southeast end of the NWHI.

A series of CRW near-real-time, twice-weekly, DHW charts (Fig. 3) shows the development of the extent of thermal stress accumulation in the North Pacific Ocean during the same time period. The original near-real-time charts are archived and web-accessible at http://www.osdpd.noaa.gov/PSB/EPS/SST/dhw_retro_2002.html. The accumulation of DHW in the NWHI region started in late July and continued into early September. Maximum DHW accumulations decreased towards the southeast in the NWHI.

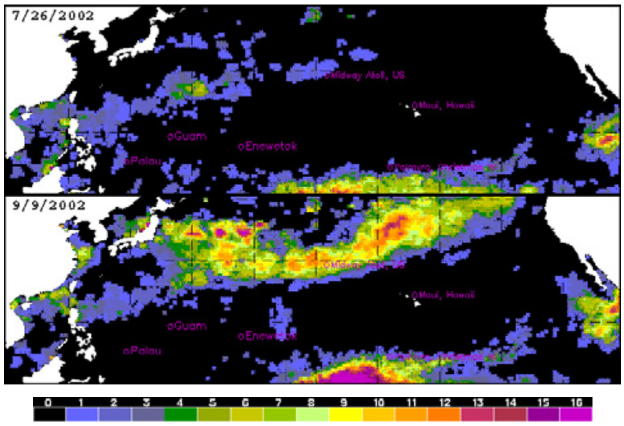

Fig. 3. CRW's near-real-time DHW charts of July 26 and September 9, 2002, showing the accumulation of thermal stress in the North Pacific Ocean during the 2002 mass coral bleaching event in the NWHI. See Fig. 2 for the location of the NWHI.

Satellite SST time series (Fig. 4) show that, among the reef areas in the NWHI region, the three northwestern-most atolls, Kure, Midway, and Pearl and Hermes, bore the worst of the thermal stress. The 50-km satellite pixels closest to these three atolls are centered at (28.5N, 178.0W), (28.5N, 177.5W), and (28.0N, 176.0W), respectively. At these three satellite pixels, the maximum DHW values during the summer of 2002 were 6.0, 7.6, and 6.4 DHWs, respectively, with the maximum HotSpot values of 1.9, 1.9, and 1.6°C.

Midway Atoll is one of the 24 selected reef sites on our Tropical Ocean Coral Bleaching Indices webpage (Fig. 1d). In early August of 2002, when the satellite SST quickly exceeded the MMM climatology value and DHW started to accumulate in a large area that included Midway Atoll (Fig. 5), an early warning for potential bleaching was issued by CRW via emails (NOAA's "coral-list") to coral reef scientists and managers in the region. Several follow-up bleaching warnings were issued when a large area in the NWHI experienced more than 4 DHWs. The elevated water temperatures were also detected by the automated *in-situ* Coral Reef Early Warning System (CREWS) buoys, operated in the area by NOAA's National Marine Fisheries Service (NMFS) Coral Reef Ecosystem Division (CRED) (Hoeke et al., 2004).

In September 2002, a field survey by CRED along 135 kilometers of prime reef habitat in the NWHI verified this mass bleaching event (Aeby et al., 2003; Hoeke et al., 2004; Kenyon et al., 2004). The cruise was scheduled before the occurrence of the bleaching event, but updated information from CRW helped CRED alter their original cruise plan to focus more attention on conducting surveys on mass coral bleaching that previously was not considered a significant threat in this region.

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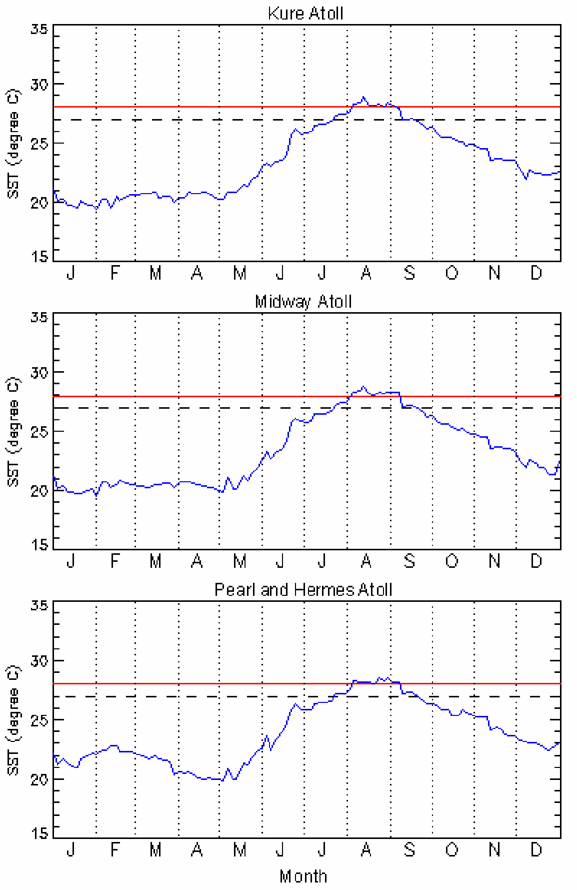

Fig. 4. CRW's near-real-time satellite SST time series charts of 2002 showing the temperature evolution at the three northwestern-most atolls of the NWHI: Kure, Midway, and Pearl and Hermes. The static MMM climatology value (black dashed lines) and MMM+1ºC (red lines) at these pixels are also plotted.

Substantial and unprecedented bleaching (greater than 20% and up to 100% of the corals) was observed on reefs at the three northwestern-most atolls, Kure, Midway, and Pearl and Hermes, with diminished bleaching in other NWHI reefs towards the southeast (Aeby et al., 2003; Kenyon et al., 2004). Bleaching was initially reported in August 2002 by the CRED-led NWHI marine debris removal team and mass bleaching was first reported in September 2002 (Aeby et al., 2003). CRW's satellite monitoring of this mass bleaching event matched very well with the *in-situ* observations in both pattern and timing of the bleaching.

Some recent noteworthy mass bleaching events detected by CRW

Since the inauguration of the CRW satellite monitoring in 1997, many mass coral bleaching events have taken place around the globe. In this section, as noteworthy events, some of these bleaching events are mentioned together with their CRW near-real-time HotSpots and DHW charts, which identified the location, spatial coverage, and intensity of the thermal stresses responsible. The 2002 mass bleaching event in the NWHI has already been discussed in the previous section and is not described in this section.

2003: A mass coral bleaching event was observed in Bermuda during the summer of 2003 (Cook CB, Smith SR, Brylewska H, de Putron S, Webster G, Strong M, pers. comm.). Of all the coral colonies recorded during a survey at the end of August and beginning of September, 21% were bleached at the rim reef sites and 19% were bleached at the lagoonal sites. Of the most affected coral species, 94% of the colonies were bleached on the rim reefs and 77% on the lagoonal reefs. Fig. 6 shows the HotSpot at its peak intensity in mid-August in the northwest Atlantic Ocean and the maximum accumulation of DHW in late-August. The maximum HotSpot and DHW values at Bermuda were 1.8°C and 9.8 DHWs, respectively.

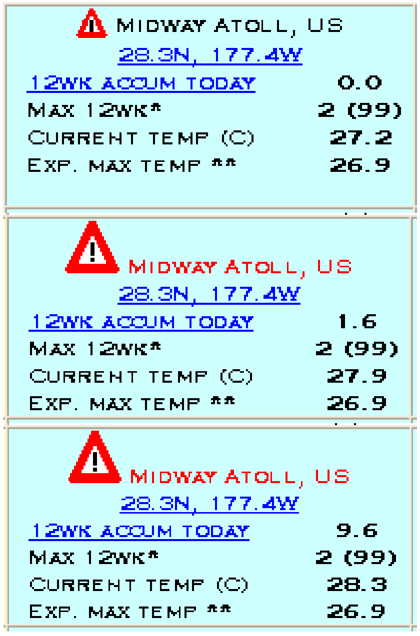

Fig. 5. CRW's Tropical Ocean Bleaching Indices webpages showing thermal stress information and related bleaching warning levels for Midway Atoll on July 22 (upper panel), August 2 (middle panel), and September 6, 2002 (lower panel).

2002: In early 2002, during the austral summer, an unprecedented mass coral bleaching event was recorded in the Great Barrier Reef (GBR), Australia (Wilkinson, 2002b; Liu et al., 2003). This bleaching event was much worse than the 1998 mass bleaching event in the GBR in terms of both intensity and spatial coverage. Almost 60% of the total GBR reef area was affected with few reefs escaping the bleaching. Up to 90% of corals were dead at the worst affected sites (Wilkinson, 2002b). Fig. 7 shows the distribution of HotSpot at its peak intensity and the maximum DHW in the GBR during early 2002. The thermal stress peaked around February 11, 2002 when widespread HotSpots over the GBR reached maximum levels between 2°C and 3°C. The maximum DHW accumulation for the region occurred just east of the

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GBR (up to 16 DHWs); while throughout the region, the maximum accumulations exceeded 10 DHWs (Liu et al., 2003).

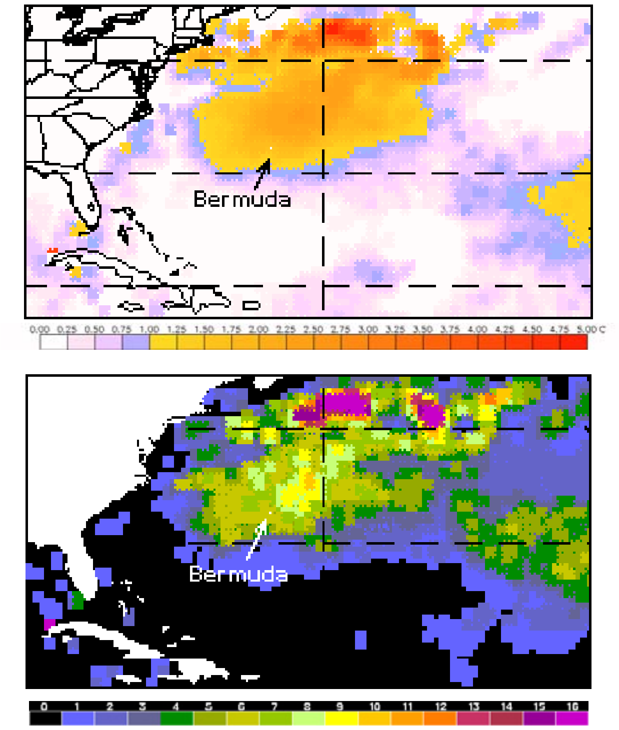

Fig. 6. CRW's HotSpot chart (upper chart) showing the thermal stress during its peak stage in mid-August 2003 in the Northwest Atlantic Ocean and DHW chart (lower chart) showing the maximum accumulation of DHW in late-August 2003.

2001: Fig. 8 shows the peak HotSpots and the maximum DHW accumulation in the Northwest Pacific Ocean during the 2001 summer, when a mass coral bleaching event occurred in the Ryukyu Islands, Japan (Strong et al., 2002). In the Ryukyu Islands, the persistent HotSpot reached its maximum intensity (around 3°C, immediately east of Okinawa) in mid-August; the accumulation of DHW started in late June and reached its maximum (more than 10 DHWs immediately east of Okinawa) in mid-September. Field observation showed that the most severe coral mortality reached 46-69% in the southern islands of Ryukyus (Dai et al., 2002).

2000: Fig. 9 shows the HotSpots at its peak intensity and the maximum DHW accumulation in early 2000 around and near Easter Island in the South Pacific Ocean. A mass coral bleaching event was observed at Easter Island during the same time period (Wellington et al., 2001). In this region, a HotSpot first appeared in early February and by March 21, a DHW value of 9 had accumulated at Easter Island. Survey at five widely distributed sites around the island revealed that an average of 85-90% of the coral colonies was affected down to a depth of 10 m (Wellington et al., 2001).

1998: A strong ENSO event occurred during 1998, coinciding with the observation of mass coral bleaching events around the globe (e.g., Wilkinson et al., 1999; Goreau et al., 2000; Wilkinson, 2002a). This world's largest coral bleaching and mortality event temporarily destroyed about 16% of the world's reefs. Large parts of the Indian Ocean, Southeast Asia and the far western Pacific were most dramatically affected, with mortality levels greater than 90% on some reefs (Wilkinson, 2002a). Fig. 10 presents a composite maximum DHW chart for 1998, showing the maximum accumulation of DHW in the global oceans during the year. The accumulation of thermal stress in the Eastern Equatorial Pacific Ocean is obviously due to the 1997-1998 El Niño event. Although the Eastern Equatorial Pacific Ocean is not a coral rich region, unprecedented global distribution of intensive thermal stress conducive to bleaching is considered to be associated with the 1997-1998 El Niño event.

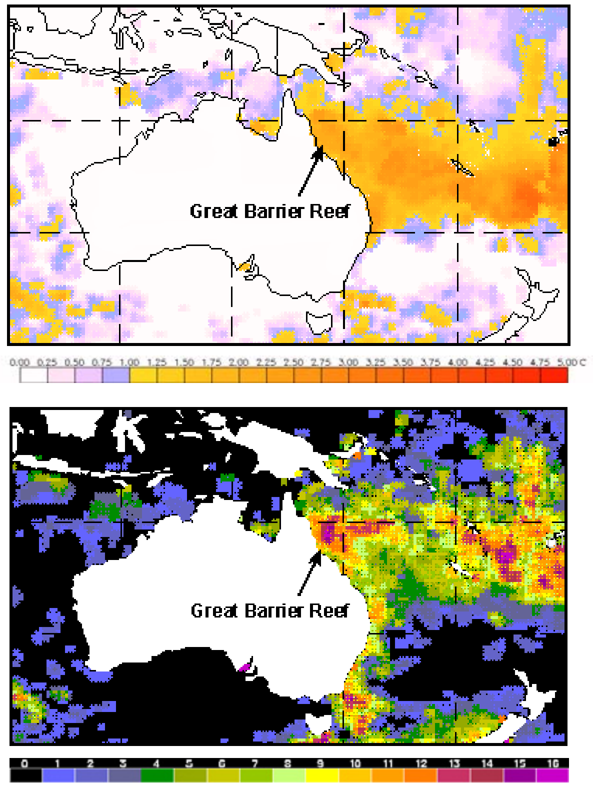

Fig. 7. CRW's HotSpot chart (upper chart) showing the thermal stress during its peak stage and DHW chart (lower chart) showing the maximum accumulation of DHW in the Great Barrier Reef, Australia and adjacent waters in early 2002.

Since 1997, CRW has issued many bleaching warnings via the internet ("e-warnings"). Verification, using the bleaching status reports sent directly to us from users in the field and obtained from the ReefBase Project of the World Fish Center, has proven most of our warnings informing users that bleaching was occurring to be correct. These warnings were issued when the values of DHW, i.e., the accumulation of thermal stress, exceeded a level of four with significant spatial coverage at the locations of interest. Detailed statistical analyses of the accuracy of our satellite HotSpot/DHW monitoring products are in progress, with results in a future publication.

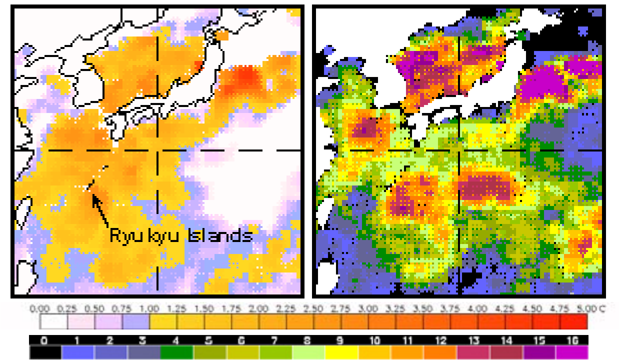

Fig. 8. CRW's HotSpot chart (left chart) showing the thermal stress during its peak stage and DHW chart (right chart) showing the maximum accumulation of DHW in the Northwest Pacific Ocean during the summer of 2001.

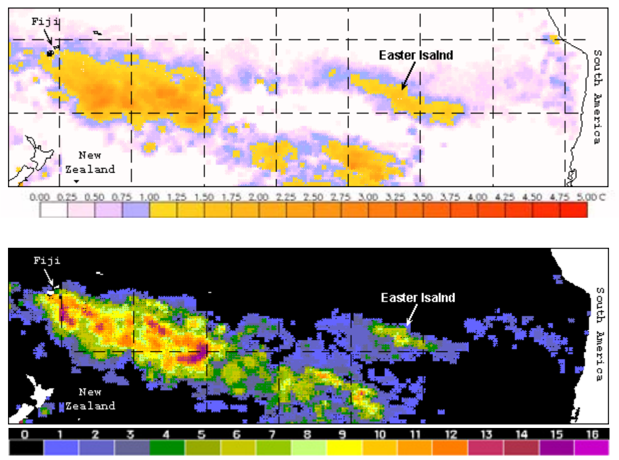

Fig. 9. CRW's HotSpot chart (upper chart) showing the thermal stress during its peak stage and DHW chart (lower chart) showing the maximum accumulation of DHW in the South Pacific Ocean in early 2000.

Growing user group of CRW satellite near-real-time coral bleaching monitoring tools

Over these past 8 years, CRW near-real-time satellite global bleaching monitoring has gained international recognition, credibility, and visibility. An early pay-off was derived from successful CRW satellite monitoring of mass coral bleaching events in the Great Barrier Reef, Australia, and accompanying *in-situ* monitoring conducted within the Great Barrier Reef in 2001. A notable science and technology arrangement was established in June 2001 between the Australian Institute of Marine Science and the Great Barrier Reef Marine Park Authority, both of The Commonwealth of Australia, and the National Oceanic and Atmospheric Administration of the United States of America regarding scientific and technical cooperation in the area of coral reefs. This achievement represents the first science and technology arrangement between the two governments. The purpose of this arrangement is to jointly pursue scientific and technical cooperation in the area of coral reef research, monitoring, and protection that further the mutual interests of the parties involved. Australia's rich experience and knowledge on the Great Barrier Reef has already played a major role in the development and improvement of both CRW satellite and *in-situ* coral bleaching monitoring.

Since 2003, CRW's near-real-time DHW data have been provided on a monthly basis to the ReefBase Project of the WorldFish Center. These DHW data are loaded into ReefBase's online GIS system as an important GIS map layer (http://www.reefbase.org). In this online GIS system, locations of reported bleaching events collected by ReefBase can be superimposed on CRW's DHW maps to correlate the locations of observed bleaching events and the values of DHW.

CRW's HotSpot and DHW charts have been used by various users in various bleaching related publications (e.g., Ministry of the Environment and Japanese Coral Reef Society, 2004; Richmond, 2002). They have also appeared in various bleaching status reports and various management, research, and educational newsletters and websites (e.g., http://www.gbrmpa.gov.au/corp_site/info_services/science/bleaching/conditions_report.html; http://www.reeffutures.org/topics/bleach/present.cfm; http://globalcoral.org/Grief%20on%20the%20Reef.htm; http://www.pbs.org/wgbh/nova/elnino/reach/coral1.html; http://globalcoral.org/Grief%20on%20the%20Reef.htm; http://www.pgd.hawaii.edu/kaams/lpreef/crdanger/over.html; http://www.eumetsat.de/en/area2/cgms/ap7-03.htm; http://www.climatescience.gov/Library/stratplan2003/final/ccspstratplan2003-chap8.htm; http://www.deh.gov.au/coasts/mpa/ashmore/volume-2/chapter4.html).

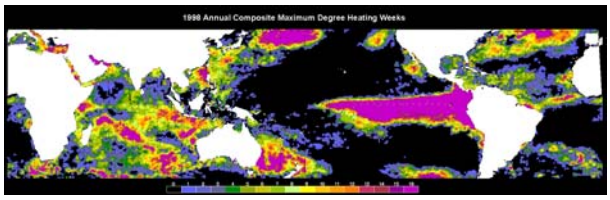

Fig. 10. CRW's composite maximum DHW chart for 1998.

Ongoing developments and future plans

CRW has been working on developing new algorithms and products to provide more accurate monitoring tools for detecting and assessing thermal stress conducive to coral bleaching and to provide more timely information to the U.S. and global coral reef communities.

At the time of writing this paper, CRW's automated Satellite Bleaching Alert (SBA) system has been developed by CRW's satellite monitoring efforts and is in the final stage of operational implementation. The SBA system is an automated coral bleaching e-mail alert system to inform users, as soon as new satellite SST data are collected and processed, of the most up-to-date status of thermal stress at the reefs of their interests. It will become the second near-real-time alert system reported in CRW's near-real-time monitoring effort, after OAR's automated Near-Real-Time Data and Expert System of CRW's *in-situ* Coral Reef Early Warning System (CREWS) Network. Once implemented, the e-mail alerts will first be available for a number of selected reef sites around the world. The system will automatically examine the updated values of near-real-time satellite SST, bleaching HotSpot, and DHW at the selected reef sites. An automated e-mail will be sent to a subscriber for a reef site only when the status level of thermal stress changes at the site. No automated e-mail will be generated if the status level remains the same, regardless of the current status level. The status level of thermal stress at selected reef sites will be updated twice per week. For each reef location, five status levels have been defined as follows: No Stress (HotSpot ≤ 0ºC), Bleaching Watch (0ºC < HotSpot < 1ºC), Bleaching Warning (HotSpot ≥ 1ºC and 0 < DHW < 4), Bleaching Alert Level 1 (HotSpot ≥ 1ºC and 4 ≤ DHW < 8), and Bleaching Alert Level 2 (HotSpot ≥ 1ºC and DHW ≥ 8). Updated stress level, SST value, HotSpot value, DHW value, and previous changes in stress level will be included in each e-mail message, along with the web addresses (URLs) leading subscribers to additional near-real-time satellite monitoring data and charts. The details of how to use the SBA e-mail alerts will be published by CRW upon system implementation. Although a free service, users will be requested to subscribe in order to receive the automated e-mail alerts. Recipients will be encouraged to provide reports on bleaching status and feedback to the SBA system. It is anticipated that additional reef sites will be added based on requests from users.

Chart-based near-real-time short-term satellite SST trends are also under development along with some other new products. These trend products give the direction and magnitude of the most recent SST changes during the past one and two weeks ending at the most recent update. Currently at 50-km resolution, CRW's satellite bleaching monitoring is capable of monitoring coral bleaching only in association with large-scale thermal stress having spatial coverage over both inshore and offshore waters. Over the next few years, higher-resolution products are planned to incorporate higher-resolution SSTs to extend the monitoring capability from basin- and regional-scale bleaching events to local- and reef-scale bleaching events. Finally, building forecasting capabilities is in CRW's future plans. Plans for this goal include incorporating numerical model simulations and monitoring other environmental parameters together with SST.

Summary

Since 1997, NOAA CRW's near-real-time satellite global coral bleaching monitoring system has become a nationally and internationally respected tool for monitoring coral bleaching. Satellite remote sensing provides global coverage, reaching remote coral reef ecosystems and providing synoptic views of the global oceans. CRW operates the only satellite global bleaching monitoring system in the world designed specifically to help coral reef managers and scientists both map and monitor anomalous SSTs and, hence, better understand and predict mass coral bleaching. New and improved products are anticipated by CRW for providing better service to both the U.S. and global coral reef communities.

The CREIOS's goal is to provide both near-real-time and long-term ecological and environmental observations and information products over a broad range of spatial and temporal scales, to understand the condition and health of, and processes influencing, coral reef ecosystems, and to assist stakeholders in making improved and timely ecosystem-based management decisions to conserve coral reefs.

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