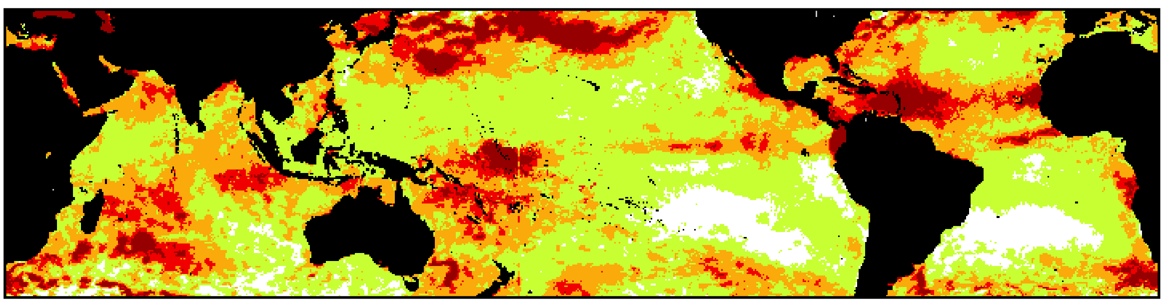
NOAA Technical Report NESDIS 143

NOAA Coral Reef Watch 50 km Satellite Sea Surface Temperature-Based Decision Support System for Coral Bleaching Management



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NOAA TECHNICAL REPORTS

National Environmental Satellite, Data, and Information Service

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NESDIS 121 Calibration of the Advanced Microwave Sounding Unit-A Radiometer for METOP-A. Tsan Mo, August 2006.

*Cover image shows the 2005 annual maximum composite of the Coral Reef Watch twice-weekly 50 km satellite Coral Bleaching Alert Area product. Intensive thermal stress in the Caribbean region during the 2005 boreal summer caused a record-breaking mass coral bleaching event.

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NOAA Coral Reef Watch 50 km Satellite Sea Surface Temperature-Based Decision Support System for Coral Bleaching Management

Gang Liu[1,2]
Jacqueline L. Rauenzahn[1,2]
Scott F. Heron[2,3]
C. Mark Eakin[1]
William Skirving[2,3]
Tyler R. L. Christensen[1,2]
Alan E. Strong[1,2]
Jianke Li[1,2]

[1] NOAA Coral Reef Watch, E/RA3, 5830 University Research Court, College Park, MD 20740, USA
[2] Global Science and Technology, 7855 Walker Drive, Suite 200, Greenbelt, MD 20770, USA
[3] NOAA Coral Reef Watch/ReefSense, 675 Ross River Rd, Townsville, Queensland 4817, Australia

Corresponding author: gang.liu@noaa.gov

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U.S. DEPARTMENT OF COMMERCE
Rebecca Blank, Acting Secretary

National Oceanic and Atmospheric Administration
Dr. Jane Lubchenco, Under Secretary of Commerce for Oceans and Atmosphere
and NOAA Administrator

National Environmental Satellite, Data, and Information Service
Mary Kicza, Assistant Administrator

Contents

Contents i
Figures ii
Executive Summary iii
1 Introduction 1
2 CRW's 50 km Global Decision Support Products and Tools 3
2.1 Sea Surface Temperature (SST) 3
2.2 SST Climatology 4
2.3 SST Anomaly 5
2.4 Coral Bleaching HotSpots 6
2.5 Degree Heating Weeks (DHW) 8
2.6 Bleaching Alert Area 9
2.7 Short-Term SST Trends 11
2.8 Monthly and Annual Composites 12
2.9 Virtual Stations 12
2.9.1 Operational Virtual Stations 13
2.9.2 Experimental Virtual Stations 14
2.10 Time Series Graphs and Data for Virtual Stations 15
2.11 Automated Satellite Bleaching Alert (SBA) E-mails 20
2.12 CRW Thermal Stress Satellite Monitoring Source Data 21
2.13 CRW Products in Google Earth Format 22
2.14 CRW Products in the ReefBase Online GIS System 23
2.15 Tutorial for Coral Reef Watch Products 24
2.16 Enhanced 50 km (E-50) Product Suite 24
2.17 Contingency 50 km Product Suite 28
3 Discussions, Conclusions, and Future Directions 28
3.1 High-Resolution Bleaching Thermal Stress Monitoring Products 29
3.2 Light Stress Damage 29
3.3 Coral Disease Outbreak Risk 30
3.4 Additional Remotely Sensed Environmental Variables 30
4 Acknowledgements 30
5 Bibliography 31

Figures

Figure 1. CRW's operational near-real-time twice-weekly global 50 km nighttime SST analysis for October 18, 2010. 4

Figure 2. CRW's operational near-real-time twice-weekly global 50 km nighttime SST Anomaly for October 18, 2010. 6

Figure 3. CRW's operational near-real-time twice-weekly global 50 km Coral Bleaching HotSpots for October 18, 2010. 7

Figure 4. CRW's operational near-real-time twice-weekly global 50 km Coral Bleaching Degree Heating Weeks for October 18, 2010. 9

Figure 5. CRW's operational near-real-time twice-weekly global 50 km Bleaching Alert Area for October 18, 2010. 10

Figure 6. CRW's experimental near-real-time twice-weekly global 50 km Short-Term SST Trends product for October 18, 2010. 11

Figure 7. Annual maximum composite of NOAA Coral Reef Watch's operational twice-weekly 50 km satellite Bleaching Alert Areas product for 2010. 12

Figure 8. Webpage of CRW's 24 operational Virtual Stations for March 4, 2013. 13

Figure 9. Google Map display of CRW's 24 operational and 227 experimental Virtual Stations for March 4, 2013. 14

Figure 10. CRW's 2010-2011 two-year time series graph for the USVI Virtual Station. 16

Figure 11. CRW's 2001-2013 multi-year time series graph for the USVI Virtual Station. 17

Figure 12. Excerpt of CRW's 2000-present time series data for the USVI Virtual Station. 19

Figure 13. Sample summary section of an automated CRW Satellite Bleaching Alert e-mail message. 21

Figure 14. Google Earth display of maximum composite of CRW's 50 km satellite DHW during the 2005 record-breaking mass coral bleaching event in the Caribbean. 23

Figure 15. ReefGIS display of the 2005 annual maximum composite of CRW's twice-weekly 50 km satellite coral bleaching Degree Heating Weeks (DHW). 24

Figure 16. Comparison of CRW's (a) operational 50 km land mask and (b) enhanced 50 km land mask for the Caribbean and surrounding regions. 25

Figure 17. Comparison of CRW's (a) operational 50 km land mask and (b) enhanced 50 km land mask for Australia and surrounding regions. 25

Figure 18. Comparison of CRW's (a) enhanced 50 km land mask and (b) operational 50 km land mask for the Caribbean on a sample composite Degree Heating Weeks image. 27

Tables

Table 1. Coral bleaching thermal stress levels based on the CRW 50 km Coral Bleaching HotSpots and DHW products. 10

Executive Summary

Coral Reef Watch (CRW), a program of the National Environmental Satellite Data and Information Service (NESDIS) of the U.S. National Oceanic and Atmospheric Administration (NOAA) and a part of the NOAA Coral Reef Conservation Program (CRCP), has been operating the world's only global satellite coral bleaching thermal stress monitoring system for the U.S. and global coral reef communities since 1997. Through more than a decade of satellite monitoring, CRW has evolved from providing a limited number of SST-based tools for coral bleaching monitoring, to implementing a decision support system (DSS) employing multiple satellite and model-based parameters.

CRW's mission is to utilize remote sensing and *in situ* tools for near-real-time and long-term monitoring, modeling and reporting of physical environmental conditions of coral reef ecosystems. With these tools, CRW assists the global community in the management, study, and assessment of impacts to coral reef ecosystems brought about by environmental change. Coral Reef Watch's operational satellite data products, such as Coral Bleaching HotSpots and Degree Heating Weeks, based on satellite sea surface temperature (SST) measurements, provide global near-real-time coral reef environmental conditions to quickly identify areas at risk of thermally-induced mass coral bleaching. Mass coral bleaching events have been well correlated with thermal stress. Prolonged high thermal stress can cause corals to lose their symbiotic algae and thus effectively starve. In the event of severe thermal stress, disease and mortality may follow. Severe bleaching events have had dramatic long-term ecological and social impacts, including loss of reef-building corals, changes in benthic habitat and in some cases, changes in reef fish populations. Thus, continuous monitoring of SST and bleaching-level thermal stress at the global scale provides reef managers, researchers and stakeholders with critical information to understand, predict and monitor the development of mass coral bleaching events. This aids coral reef managers by providing the ability to make informed decisions about management actions associated with high levels of coral stress. It also enables scientists and managers to gather bleaching data in a more resource efficient manner by targeting *in situ* surveys during and after mass coral bleaching events.

This report provides an overview of CRW's operational twice-weekly 0.5 degree (approximately 50 km spatial resolution) satellite coral bleaching thermal stress monitoring product suite, representing CRW's heritage product suite and the core of CRW's current DSS for much of the last decade, along with some experimental products and a major enhancement associated with the operational product suite. CRW's products are disseminated and delivered through various mechanisms and formats to satisfy different user needs and backgrounds.

To address requests from coral reef managers and scientists for their ever growing management and research needs, CRW is developing a new-generation DSS, taking advantage of advances in satellite technologies for measuring environmental variables, the availability of multiple satellites and sensors, model-based evaluations of observations and forecasts, and advances in coral physiological and ecological research. This report provides a brief introduction to CRW's new-generation coral bleaching thermal stress monitoring products and other planned efforts that will provide advanced tools for managers to better protect coral reefs in a changing climate.

1 Introduction

Coral reefs, the rainforests of the ocean, have taken thousands of years to form. However, over the past decades, coral reefs have faced unprecedented, dramatic increases in hazards and threats, resulting in the rapid decline of many coral habitats worldwide. With the increasing occurrence and severity of devastating mass coral bleaching caused by elevated sea surface temperature (SST), bleaching has been one of the most significant contributors to increased deterioration and death of coral reef ecosystems (Wilkinson, 2008).

Coral bleaching occurs when the symbiotic relationship between algae (zooxanthellae) and their host coral breaks down under various environmental stresses (Jaap, 1997; Jokiel and Coles, 1990). As a result, the host expels its zooxanthellae, exposing its white calcium carbonate skeleton, and the affected coral colony pales in color or becomes stark white. This is known as "bleaching." Anomalously warm water temperatures have been observed to be one of the major causes of mass coral bleaching worldwide. Ambient water temperatures as little as 1 to 2 °C above a coral's tolerance level, indicated by summer monthly mean temperatures, have caused coral bleaching (Berkelmans and Willis, 1999; Reaser et al., 2000). Corals that are partially to totally bleached for long periods often die. Severe bleaching events have dramatic long-term ecological and social impacts, including loss of reef-building corals, changes in benthic habitat, and, in some cases, changes in fish populations on the reef (Munday et al., 2008). Even under favorable conditions, it can take decades for severely bleached reefs to fully recover (Wilkinson, 2008). The timing of the peak bleaching season varies among ocean basins and hemispheres but is generally during the local summertime (or warmest months of the year). The peak season is July-September for the northern Atlantic and Pacific Oceans, and January-March for the southern Atlantic and Pacific. The peak is April-June for the northern Indian Ocean and January-April for the southern Indian Ocean. Near the equator, there are often two potential bleaching “seasons” during the boreal spring and fall, when the sun is directly overhead in the tropical regions.

The need for improved understanding, monitoring and prediction of coral bleaching is imperative. Satellite remote sensing provides synoptic views of the global oceans in near-real-time and monitors both easily accessed reefs as well as remote reef areas unfrequented or inaccessible to humans and *in situ* monitoring. It has become an essential tool for coral reef managers and scientists. As early as 1997, NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) began producing web-accessible, satellite-derived near-real-time SST-based products for monitoring thermal conditions around the globe to pinpoint areas where corals are at risk for thermally-induced mass coral bleaching and to assess the intensity of bleaching (see http://celebrating200years.noaa.gov/magazine/coral_tech/welcome.html). The world’s first near-real-time global satellite coral bleaching thermal stress monitoring product, Coral Bleaching HotSpots, was released experimentally by NOAA in 1997 (Strong et al., 1997). It evolved into a crucial part of the NOAA Coral Reef Watch (CRW) program in 2000 (Strong et al., 2004; Liu et al., 2005). Building on this initial framework, CRW began developing a decision support system (DSS) for coral reef management in 2005, when a suite of core satellite coral bleaching thermal stress monitoring products became operational. Since that time, CRW has continued to expand and upgrade its DSS.

CRW’s satellite thermal stress monitoring technique has been successful in now-casting coral bleaching episodes around the globe since its inauguration (e.g., Goreau et al., 2000; Wellington et al., 2001; Strong et al., 2002; Liu et al., 2003; Coral Reef Watch, 2003; Liu et al., 2005; Strong et al., 2006; Skirving et al., 2006b; Eakin et al., 2010; Liu et al., 2012). As a result, during the period September 2002 to February 2003, most of CRW's core products were gradually transitioned from "experimental" to "operational" status. The "operational" products are supported and delivered by NESDIS on a 24-hour/7-day basis, permitting reliable and regular global monitoring of environmental conditions harmful to corals.

CRW's mission is to utilize remote sensing and *in situ* tools for near-real-time and long-term monitoring, modeling, and reporting of physical environmental conditions of coral reef ecosystems. To meet the ever-growing needs of managers and scientists for accurate and timely information on coral reef ecosystems, CRW has evolved from providing a limited number of satellite SST-based tools, to implementing a web-based global DSS monitoring multiple satellite and model-based parameters for coral reef management.

This technical report provides an overview of CRW's twice-weekly 0.5 degree (approximately 50 km spatial resolution, hereafter "50 km") satellite thermal stress monitoring product suite for coral bleaching. This is CRW's heritage product suite and forms the core of CRW's current DSS. It includes: SST, SST Anomaly, Coral Bleaching HotSpots, coral bleaching Degree Heating Weeks (DHW), Bleaching Alert Area, Virtual Stations, and a Satellite Bleaching Alert (SBA) email system. These products are based on operational twice-weekly NOAA/NESDIS composite nighttime Polar Operational Environmental Satellites (POES) Advanced Very High Resolution Radiometer (AVHRR) SSTs at 50 km resolution. They are described individually in the following sections and can be accessed online at: http://coralreefwatch.noaa.gov. Data and images are available for free to the public. Online tutorials and Liu et al. (2003) demonstrate how to use the DSS.

All products described in the report are currently updated twice-weekly every Monday morning (using observations from the previous Thursday through Sunday) and Thursday morning (using observations from the previous Monday through Wednesday), U.S. Eastern Time. Prior to May 3, 2007, the products were updated every Tuesday morning (using observations from the previous Saturday through Monday) and Saturday morning (using observations from the previous Tuesday through Friday), U.S. Eastern Time. This change in product delivery timing was undertaken to provide users around the globe with access to the twice-weekly monitoring updates during the standard working week. Data and images are date-stamped with the end-date of the twice-weekly period.

Most products in CRW's twice-weekly 50 km product suite are operational; the rest are experimental or are currently being transitioned from experimental to operational status. A CRW experimental product is usually processed and generated on developmental machines after it is first released to users. After then passing through a rigorous quality control process, including validation using *in situ* observations and strong user support, an experimental product is transitioned to an operational product facility at the NESDIS Office of Satellite and Product Operations (OSPO), where it is processed and generated on operational machines and maintained on a 24-hour, 7-day (24/7) basis, to ensure continuous availability. Products that require major improvements after initial release usually remain in experimental status for longer periods of time, going through various, additional developmental phases, where user feedback is incorporated, until acceptable results are achieved. Other products that are either preliminary products for guiding further research activities (e.g., CRW's Sea Surface Wind – Doldrums product, not described in this report), or that serve as "bridging products" while CRW awaits new-generation satellite products or data streams at NOAA or external to the bureau, are not transitioned to operational status (e.g., CRW's Enhanced 50 km product suite, or E-50, described in Section 2.16).

The CRW team at NOAA/NESDIS that develops and generates these monitoring products comprises scientists from the Center for Satellite Applications and Research (STAR, formerly the Office of Research and Applications (ORA)) and from OSPO (formerly the Office of Satellite Data Processing and Distribution (OSDPD)).

2 CRW's 50 km Global Decision Support Products and Tools

2.1 Sea Surface Temperature (SST)

NOAA has been deriving SST with the use of satellite-based instruments since 1972. Monitoring SST from earth-orbiting infrared radiometers has had a wide impact on marine science. One of the principal sources of global infrared data for SST is the AVHRR carried on NOAA's POES and the European Organisation for the Exploitation of Meteorological Satellites' (EUMETSAT) MetOp satellites. AVHRR, available since 1978, is a broad-band, four, five or six channel (depending on the model) scanner, sensing in the visible, near-infrared, middle infrared, and thermal infrared portions of the electromagnetic spectrum. AVHRR measurements of temperature originate from a very small depth of the ocean surface (the "skin"). The skin layer is approximately 20 micrometers (μm) deep at AVHRR's 10-12 micrometer spectral waveband (http://ghrsst-pp.metoffice.com/pages/sst_definitions/). The POES satellite system offers the advantage of daily global coverage by making near-polar orbits roughly 14 times daily. *In situ* SST from buoys (drifting and moored) has been used operationally to maintain accuracy of satellite SST by removing biases and compiling statistics (McClain et al., 1985; Strong, 1991; Montgomery and Strong, 1995; Strong et al., 2000).

The CRW operational near-real-time nighttime SST analysis product is a gap-filled, twice-weekly composite of global satellite nighttime AVHRR SST fields at 50 km resolution. Surface temperature during the daytime can differ substantially from the temperature experienced by corals (at depth), when the vertical mixing caused by environmental conditions (e.g., wind, currents, waves) is lacking during clear, warm days; nighttime temperatures are stable with depth in the upper water column (Donlon et al. 2002). It is of note that conditions conducive to coral bleaching include low wind, weak currents and clear skies ('bleaching weather', Skirving et al., 2006a), of which the first two indicate a lack of vertical mixing (and therefore a potential difference between temperatures at surface and at depth). Nighttime-only satellite SST observations are used to eliminate the issue of surface warming during the day and to avoid contamination from solar glare. Compared with daytime SST and day-night blended SST, nighttime SST provides more conservative and stable estimates of thermal stress at the depth of corals that is conducive to coral bleaching. Nighttime SSTs also compare favorably with *in situ* SSTs at one meter depth (Montgomery and Strong, 1995), especially at times when bleaching occurs. The 50 km resolution data are derived by averaging multiple temperature observations (weighted by distance from pixel center, conditionally out to a maximum of 150 km), which are based on 4 km AVHRR Global Area Coverage (GAC) SSTs acquired daily (Skirving et al., 2006b). In locations where cloudy conditions remain for extended periods of time, resulting in no new temperature observations, the most-recent high-quality SST value persists.

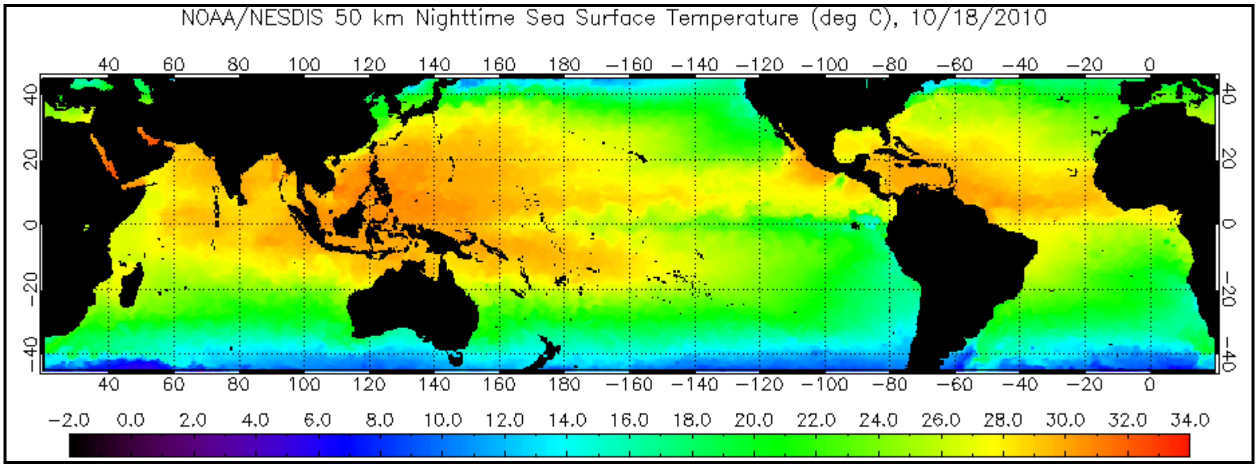

Figure 1. CRW's operational near-real-time twice-weekly global 50 km nighttime SST analysis for October 18, 2010.

A sample chart of CRW's twice-weekly 50 km SST product (Fig. 1) demonstrates the global coverage of the SST product. The color range of temperatures displayed is -2.0 to 34.0 °C. Ice data from the NOAA National Center for Environmental Prediction (NCEP) have been used to identify the location of sea ice (not shown in Fig. 1) since April 28, 1998.

The SST product became experimental in 1997 for producing the Coral Bleaching HotSpots product (described later in this report) and was upgraded to an operational product in September 2002. Data and images of both near-real-time and archived SST fields are available from the CRW website, along with animations of SST images for the most-recent six-month time period. The SST product can be accessed directly at: http://coralreefwatch.noaa.gov/satellite/current/products_sst.html.

To extend CRW's satellite SST data record back to earlier years, retrospective 1984-1998 monthly mean satellite SST analyses at 1/3 degree (~36 km) resolution were produced and posted online by CRW at: http://www.ospo.noaa.gov/Products/ocean/sst/monthly_mean.html (accessible via CRW's website). Source data for the monthly SST time series were reprocessed 36 km nighttime-only weekly mean satellite SST data from the Rosenstiel School of Marine and Atmospheric Science (RSMAS) at the University of Miami and were based on the Multi-Channel SST (MCSST) from NESDIS' POES AVHRR data (Gleeson and Strong, 1995).

2.2 SST Climatology

A long-term average (i.e., climatology) is required to provide context for individual measurements; e.g., how individual values compare with what might be 'expected' (the average) at a particular location for that time of year. It also provides a reference for identifying thermal stress conducive to coral bleaching.

The production of monthly mean 36 km SST data, described at the end of Section 2.1 (Sea Surface Temperature), enabled the development of a monthly mean SST climatology derived solely from satellite nighttime SST observations, and at a higher spatial resolution (36 km) than any previous global SST climatology (Strong et al., 1997). The release of these data in mid-1996 included the years 1985-1993.

The monthly mean SST climatology was derived by averaging these satellite SSTs during the time period 1985-1993. Observations from the years 1991 and 1992 were omitted due to the aerosol contamination from the eruption of Mt. Pinatubo. The 36 km climatology was re-gridded to the 50 km resolution of the near-real-time SST analysis described in Section 2.1. The seven-year monthly climatology was developed at NOAA/NESDIS/STAR (formerly ORA) before being delivered to NESDIS/OSPO (formerly OSDPD) for implementation.

For comparison with individual twice-weekly SST measurements, daily SST climatology values were constructed by linear interpolation of adjacent monthly climatology data through time. Each monthly climatology was prescribed as the daily climatology for the 15th day of that month. A daily climatology value was derived by linearly interpolating between the prior (P) and subsequent (S) monthly climatology values (T_P and T_S, respectively):

$$\text{Daily\_SST\_climatology} = \text{day\_fraction}*(T_P - T_S) + T_P,$$

where

$$\text{day\_fraction} = (t - t_P) / (t_S - t_P)$$

is the ratio of the number of days between the targeted day (t) and the 15th day of the prior month (t_p), to the number of days between the 15th day of the prior month and the 15th day of the subsequent month (t_s). For example, the daily SST climatology for May 25th, at a location where the May climatology is 26 °C and the June climatology is 30 °C, is calculated by:

day_fraction = (May 25th – May 15th)/(June 15th – May 15th) = 10/31 = 0.32258,
Daily_SST_climatology = 0.32258 * (30 °C - 26 °C) + 26 °C = 27.3 °C.

For producing CRW's operational satellite thermal stress monitoring products (HotSpots and DHW, described in Sections 2.4 and 2.5, respectively), a specialized climatology, the Maximum of the Monthly Mean (MMM) SST climatology, was derived from the 12 monthly mean climatologies by taking the highest value for each pixel.

Each of the monthly, daily and MMM SST climatologies are static in time but vary in space (Strong et al., 1997). These operational monthly mean climatologies and MMM are available as images and HDF data files on the CRW website at: http://coralreefwatch.noaa.gov/satellite/hdf/index.html.

2.3 SST Anomaly

CRW's near-real-time global SST Anomaly product quickly pinpoints regions of elevated SSTs throughout the world's oceans. It is especially valuable for tropical regions where most of the world's coral reef ecosystems thrive. It is also very useful in assessing ENSO (El Niño-Southern Oscillation) development, monitoring tropical cyclone "wake" cooling, and observing major shifts in coastal upwelling. CRW's SST Anomaly is produced with the same spatial (50 km) and temporal (twice-weekly) resolution as the SST product.

The SST Anomaly is calculated by subtracting the daily SST climatology for the last day of the twice-weekly period from the SST. A positive anomaly means that the current SST is warmer than expected at that location for that time of year; a negative anomaly means it is cooler than the climatological value. The formula for obtaining the anomaly is:

SST_anomaly = SST - Daily_SST_climatology

A sample chart of CRW's twice-weekly 50 km SST Anomaly product (Fig. 2) shows positive anomalies in the Indian, western Pacific and northern Atlantic Oceans, with cooler than average values in the eastern Pacific Ocean. These color charts are produced with a range of -5.0 to +5.0 °C.

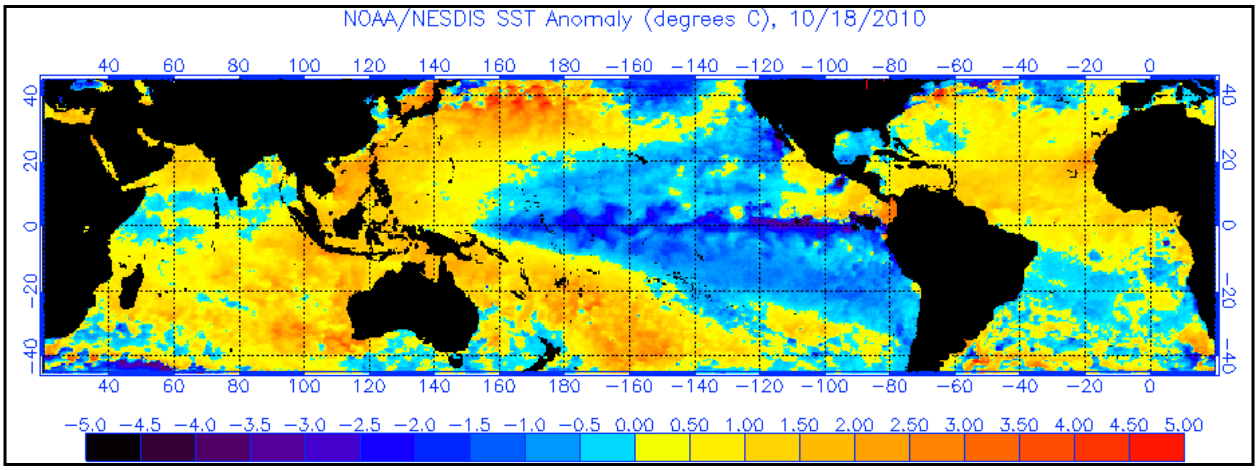

Figure 2. CRW's operational near-real-time twice-weekly global 50 km nighttime SST Anomaly for October 18, 2010.

The SST Anomaly product became operational in September 2002. Data and images of the near-real-time and archived SST Anomaly products are available from the CRW website, along with the animations of SST anomaly images for the most-recent six-month time period. The SST Anomaly product can be accessed at: http://coralreefwatch.noaa.gov/satellite/current/products_ssta.html.

Charts of retrospective 1984-1998 monthly mean SST anomalies at 36 km resolution are available online at: http://www.ospo.noaa.gov/Products/ocean/sst/monthly_mean_anom.html (accessible via CRW's website), extending CRW's 50 km data record back to earlier years. This dataset is based on the retrospective 36 km SST and the monthly mean 36 km climatology described in Sections 2.1 and 2.2, respectively.

2.4 Coral Bleaching HotSpots

Corals are vulnerable to bleaching when water temperature exceeds the temperatures normally experienced in the hottest month (Glynn and D'Croz, 1990). CRW's Coral Bleaching HotSpots product was released experimentally in early 1997 as the world's first satellite-based coral stress monitoring product (Strong et al., 1997), using a technique based on earlier work by Goreau and

Hayes (1994). CRW's HotSpot is produced with the same spatial (50 km) and temporal (twice-weekly) resolution as the SST product.

The HotSpots product measures occurrence and magnitude of instantaneous thermal stress, potentially resulting in coral bleaching. It is an anomaly product based on an atypical climatology – the climatological mean SST of the hottest month (i.e., MMM SST climatology described in Section 2.2; Liu et al., 2003, 2005; Skirving et al., 2006b). Glynn and D'Croz (1990) showed that temperatures exceeding 1 °C above the usual summertime maximum are sufficient to cause stress to corals. Based on this study, the MMM SST climatology was selected as the threshold for monitoring coral thermal stress. CRW's 50 km HotSpot value is calculated as:

$$\text{HotSpot} = \text{SST} - \text{MMM\_SST\_climatology}; \ \text{HotSpot} \geq 0\ ^\circ\text{C}.$$

As the HotSpots product is designed to show the occurrence and distribution of thermal stress conducive to bleaching, all negative values are set to zero, and only positive values are derived. Note that MMM_SST_climatology is static in time but varies in space.

A HotSpot value of 1.0 °C or more indicates thermal stress leading to coral bleaching (Glynn and D'Croz, 1990). To highlight this threshold on a CRW HotSpots chart (Fig. 3), non-zero HotSpot values below 1.0 °C are shown in purple, and HotSpots of 1.0 °C or greater range from yellow to red. The color range of HotSpots displayed on the charts is 0.0 to +5.0 °C.

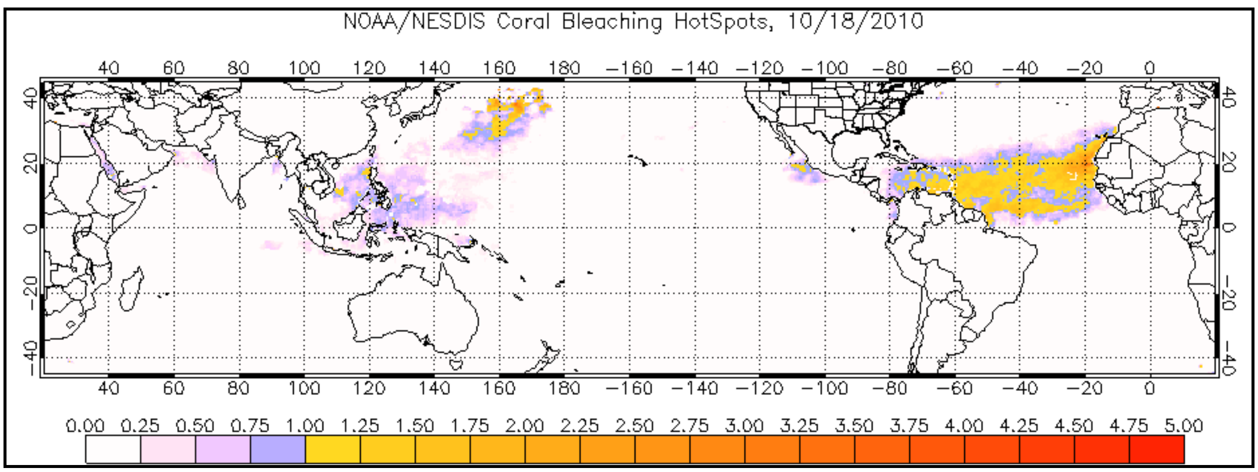

Figure 3. CRW's operational near-real-time twice-weekly global 50 km Coral Bleaching HotSpots for October 18, 2010.

Data and images of both near-real-time and archived HotSpots are available from the CRW website, along with animations of images for the most-recent six-month time period. The HotSpots product can be accessed directly at: http://coralreefwatch.noaa.gov/satellite/current/products_hotspot.html.

In 1998, the world's coral reefs experienced abnormally warm SSTs associated with a major El Niño-Southern Oscillation (ENSO) event, causing widespread mass bleaching globally. Fortuitously, CRW's HotSpots product was experimentally released online in 1997 right before this global bleaching event. A special webpage (http://www.ospo.noaa.gov/Products/ocean/cb/hotspots/1998anim.html) containing customized animations and images of HotSpots was produced by CRW to demonstrate the correlation of satellite measured coral bleaching thermal stress and *in situ* coral bleaching observations collated by Dr. Alan Strong (a NOAA/NESDIS satellite oceanographer who initially developed the NESDIS satellite coral bleaching thermal stress monitoring products and eventually established the CRW program, see: http://celebrating200years.noaa.gov/magazine/coral_tech/welcome.html) from an informal network of coral reef researchers and observers. These reports and early alerts were overlaid on the 1998 animations and images posted on the webpage.

The Hotspots product became CRW's first operational coral bleaching thermal stress product in September 2002.

2.5 Degree Heating Weeks (DHW)

While the Coral Bleaching HotSpots product provides an instantaneous measure of thermal stress, evidence suggested that mass coral bleaching is caused by prolonged periods of thermal stress (Glynn and D'Croz, 1990). In 2000, CRW developed and implemented a satellite-based coral bleaching Degree Heating Weeks (DHW) product for monitoring the accumulation of instantaneous thermal stress measured by HotSpots (Liu et al., 2003; Liu et al., 2005; Skirving et al., 2006b; Strong et al., 2006). Published with the same spatial (50 km) and temporal (twice-weekly) resolution as the SST product, CRW's DHW is a cumulative measure of thermal stress intensity and duration during the most-recent 12-week period. It is expressed in the unit °C-weeks. One week of HotSpot values at 2 °C and two weeks of HotSpot values at 1 °C would contribute 2 °C-weeks, equally, to a DHW accumulation.

Based on the finding that temperatures exceeding 1 °C above the usual summertime maximum are sufficient to cause thermal stress to corals (Glynn and D'Croz, 1990), CRW defined MMM+1 °C as the bleaching threshold temperature for accumulating thermal stress (i.e., only HotSpot values ≥ 1 °C are accumulated in the DHW). For example, during a 12-week time period when the non-zero weekly Hotspot values are 0.5, 1, 2, 0.9, and 1 °C, the resulting DHW value is 4 °C-weeks, with no contribution from 0.5 and 0.9 °C. However, during a 12-week time period when the non-zero weekly HotSpot values are 1, 2, 2, and 1 °C (all of which are ≥ 1 °C), all of the HotSpot values are accumulated, and the resulting DHW value is 6 °C-weeks.

Because each CRW twice-weekly HotSpot covers only one-half of a week, the DHW accumulates 24 twice-weekly HotSpot values in a 12-week time period. The summation of these 24 twice-weekly HotSpot values has the unit °C-half-weeks, or 0.5 °C-weeks. The formula for calculating a DHW, which has the unit °C-weeks, from the twice-weekly HotSpots ≥ 1 °C, is:

$$\text{DHW} = 0.5 * \text{sum of previous 24 twice-weekly HotSpot, HotSpot} \geq 1\ {}^{\circ}\text{C}.$$

Since the DHW is a 12-week accumulation of HotSpots, it is possible for a location to have a non-zero DHW value when the HotSpot value is currently less than 1 °C or even at 0 °C. It indicates that there has been thermal stress at that location within the most-recent 12 weeks, but local conditions are not currently stressful for corals. Prior exposure to thermal stress may still have adverse impacts on the corals, although recovery may be underway.

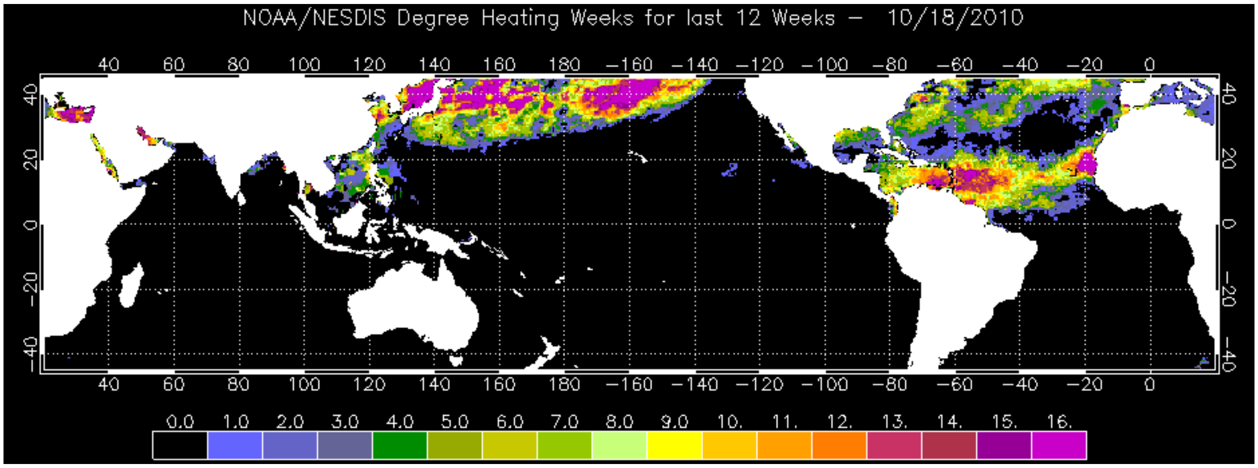

Figure 4. CRW's operational near-real-time twice-weekly global 50 km Coral Bleaching Degree Heating Weeks for October 18, 2010.

A sample chart of CRW's twice-weekly 50 km DHW product (Fig. 4) shows accumulated thermal stress in the Caribbean Sea. The range displayed is 0.0 to 16.0 °C-weeks.

The DHW product became operational in September of 2003 and can be found at: http://coralreefwatch.noaa.gov/satellite/current/products_dhw.html. Data and images of both near-real-time and archived DHW are available, along with animations of DHW images for the most-recent six-month time period.

Field observations (many of which are subjective measurements presented as informal reports) with corresponding satellite data are only available for a limited number of years (e.g., Goreau et al., 2000; Wellington et al., 2001; Strong et al., 2002; Liu et al., 2005; Coral Reef Watch, 2003; Liu et al., 2003; Skirving et al., 2006b; and Eakin et al., 2010). These observations revealed a strong correlation between observed bleaching intensity and CRW's DHW values. Significant (or "massive"), visible coral bleaching usually occurs when DHW values reach 4 °C-weeks. By the time DHW values reach 8 °C-weeks, widespread bleaching is likely and significant mortality can be expected. Since its inauguration in 2000, the DHW product has been successfully generating satellite bleaching warnings and alerts. These DHW values have been used to establish these warnings and alerts (shown below).

Retrospective DHW charts for 1998-1999 were produced based on CRW's archived twice-weekly 50 km HotSpots dating back to 1997. This analysis demonstrated the effectiveness of the DHW product, on a global scale, in detecting the severe coral bleaching thermal stress experienced during the 1998 global mass coral bleaching event (discussed in Section 2.4). These images are posted at: http://www.ospo.noaa.gov/Products/ocean/cb/dhw/1998-1999.html (which can be accessed via CRW's website).

2.6 Bleaching Alert Area

The CRW Coral Bleaching Alert Area product summarizes the current thermal stress conditions and provides location, coverage, and potential risk level of current bleaching thermal stress. The thermal stress levels (Fig. 5) are defined based on values of the Coral Bleaching HotSpots and

DHW products (Table 1). The Bleaching Alert Area product is published with the same spatial (50 km) and temporal (twice-weekly) resolution as the SST product.

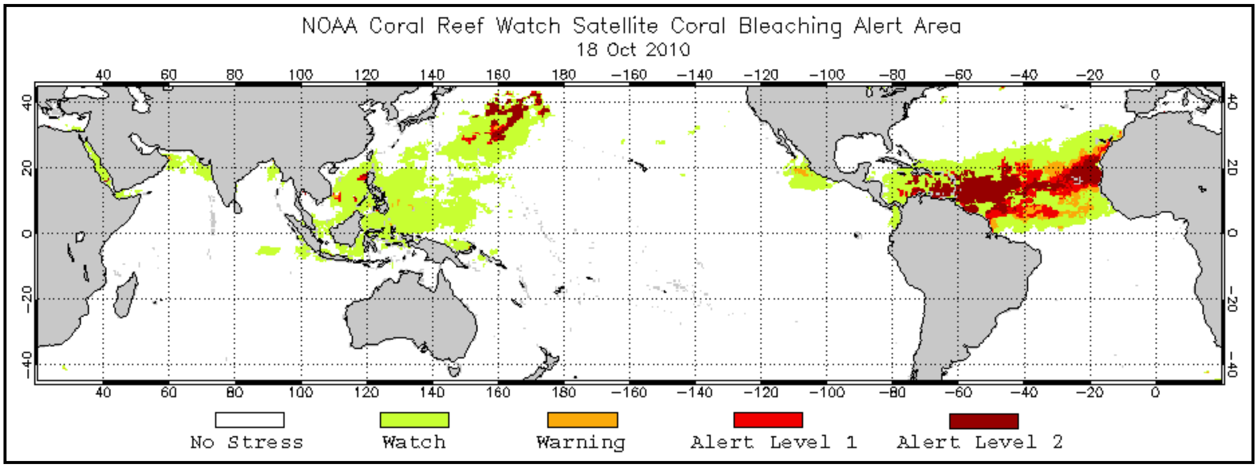

Figure 5. CRW's operational near-real-time twice-weekly global 50 km Bleaching Alert Area for October 18, 2010.

Stress Level	Definition	Effect
No Stress	HotSpot ≤ 0	--
Bleaching Watch	0 < HotSpot < 1	--
Bleaching Warning	1 ≤ HotSpot and 0 < DHW < 4	Possible Bleaching
Bleaching Alert Level 1	1 ≤ HotSpot and 4 ≤ DHW < 8	Bleaching Likely
Bleaching Alert Level 2	1 ≤ HotSpot and 8 ≤ DHW	Mortality Likely

Table 1. Coral bleaching thermal stress levels based on the CRW 50 km Coral Bleaching HotSpots and DHW products.

If a location has a status level of "No Stress" or "Bleaching Watch," it is still possible for the corresponding DHW value to be greater than 0 °C-week. This condition simply means that there has been thermal stress at that location sometime over the most-recent 12 weeks, but the local conditions are not currently stressful for corals, should they exist in that location. Previous thermal stress exposure may still have adverse impacts on the corals, although recovery may be underway.

The Bleaching Alert Area product was implemented in April 2009 and became operational in July 2012. Data and images of both the near-real-time and archived Bleaching Alert Area product are available from the CRW website (http://coralreefwatch.noaa.gov/satellite/baa/index.html), along with animations of its images for the most-recent six-month time period.

2.7 Short-Term SST Trends

While SST monitoring measures instantaneous thermal condition, SST trends over a given short period of time provide information on the rate and direction of changes in thermal condition and potential changes in the immediate future. An experimental 21-day Short-Term SST Trends product based on the latest three weeks of CRW's operational twice-weekly 50 km satellite SSTs was added to CRW's DSS in 2009. Six consecutive twice-weekly global SSTs over the last 21 days (three weeks) are included in the calculation. Linear regression is used to derive trend value for each pixel individually.

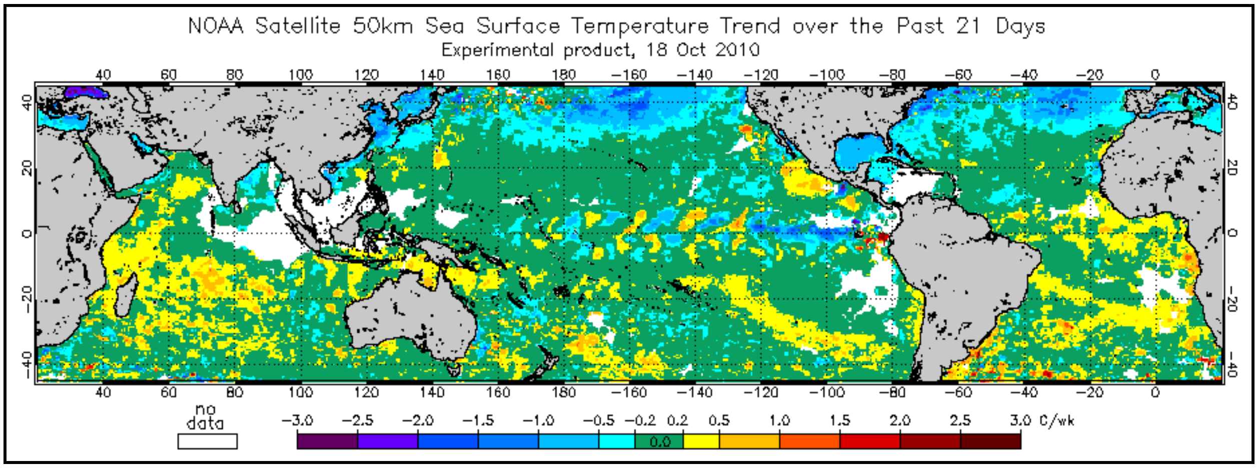

Figure 6. CRW's experimental near-real-time twice-weekly global 50 km Short-Term SST Trends product for October 18, 2010.

A sample chart of the twice-weekly 50 km Short-Term SST Trends product (Fig. 6) shows recent warming in the western Indian Ocean and recent cooling in the equatorial eastern Pacific Ocean. The color range of temperature change rate displayed on the chart is -3.0 to 3.0 °C/week.

Areas where no new satellite SST observations were available during the first week (i.e., the first two twice-weekly values) and/or the last week (i.e., the last two twice-weekly values) of the 21-day time period are excluded (white pixels in Fig. 6). Persistent cloud cover prevents the AVHRR sensor onboard the POES from observing SST. As a result, large patches of white pixels most likely indicate areas with persistent cloud.

Regions with near-zero or statistically insignificant SST trends are identified in the product by green pixels. Trends at these pixels are either too small (ranging between -0.2 and 0.2 °C) or fail the test for the 0.2 significance level (probability level of 0.2) using a two-tailed Student's t-test with four degrees of freedom.

Implemented in June 2010, the Short-Term SST Trends product described here is the second version of the product, which replaced the first SST Trends product launched in October 2009. Data and images of the near-real-time and archived Short-Term SST Trends product are available from the CRW website (http://coralreefwatch.noaa.gov/satellite/ssttrends/index.html).

2.8 Monthly and Annual Composites

CRW provides users with different summaries of thermal stress conditions, including monthly, annual, and current-year (e.g. 2013) year-to-month minimum, maximum, and mean composites of CRW's operational twice-weekly 50 km SST, SST Anomaly, Coral Bleaching HotSpots, DHW, and Bleaching Alert Areas. Thermal stress occurs and peaks at different times of the year in different regions, and with differing intensity. These composites allow mapping of the full spatial extent and maximum intensity of individual thermal stress events, as well as identification of possible teleconnections between thermal stress events occurring in different regions, such as the teleconnection between ENSO events and the occurrence and intensity of associated thermal stress events in the western Pacific, Atlantic, and Indian Oceans, which usually occur out-of-phase with each other (e.g. Fig. 7).

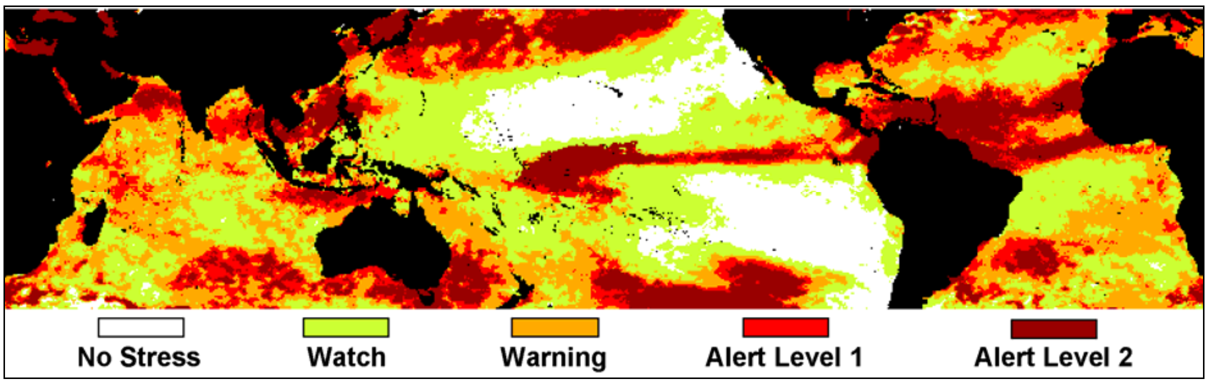

Figure 7. Annual maximum composite of NOAA Coral Reef Watch's operational twice-weekly 50 km satellite Bleaching Alert Areas product for 2010, indicating areas where bleaching thermal stress levels were observed (Table 1).

The composite product, which includes data and images from 2001-present, was launched experimentally in November 2009 on the CRW website (http://coralreefwatch.noaa.gov/satellite/current_composites/index.html), and continues to be updated on monthly and annual timeframes.

2.9 Virtual Stations

CRW's Virtual Stations are fully based on CRW's satellite products that provide near-real-time location-specific monitoring information on thermal stress conducive to coral bleaching for select coral reef sites around the world. Using remotely sensed satellite data, they provide many near-real-time and long-term measurements and analyses normally associated with *in situ* instrumentation at field stations, hence the name "Virtual Stations". The information is extracted from the CRW near-real-time 50 km satellite global SST product suite, including the various derived indices of coral bleaching thermal stress (see Sections 2.1, 2.3, 2.4 and 2.5). At present, CRW has 24 operational and 227 experimental Virtual Stations that are updated twice-weekly. Users are encouraged to email requests for other reef locations to: coralreefwatch@noaa.gov, providing the rationale for the addition of Virtual Station sites. CRW is incorporating *in situ* data available in near-real-time at select long-term monitoring locations at or near some Virtual

Stations to complement and for comparison with CRW's satellite data. CRW's Virtual Stations product is available at: http://coralreefwatch.noaa.gov/satellite/current/products_vs.html

2.9.1 Operational Virtual Stations

In early 2000, CRW released 24 experimental Virtual Stations across the world's tropical oceans (Liu et al., 2001). After being endorsed by coral reef managers worldwide, these 24 stations became CRW's operational Coral Bleaching Virtual Stations in 2003 (http://www.osdpd.noaa.gov/ml/ocean/cb/virtual_stations.html). A sample webpage displaying near-real-time satellite coral bleaching thermal stress information for the 24 stations (Fig. 8) indicates an alert level of Bleaching Watch at several locations. Information listed for each station includes the name of the reef site associated with the station, current thermal stress level, current DHW value, historical maximum DHW value and its year of occurrence, current SST value, and the MMM SST climatology value for that site. The five status levels of thermal stress shown on the Virtual Stations page are the same as those for the Bleaching Alert Area product (Table 1). A map showing the satellite pixel (Virtual Station) and its targeted reef site is accessible by clicking on the reef name. The map page also provides links to other monitoring products, including current satellite ocean surface winds, SST time series, and the Satellite Bleaching Alerts online subscription. Regional DHW and SST charts for each station are accessible by clicking on "Current DHW" and "Current SST," respectively.

Atlantic Ocean	Pacific Ocean		Indian Ocean
Bermuda No Stress Current DHW 0.0 Hist Max DHW 7.5(1998) Current SST(C) 19.3 Max Month SST 27.2	**Midway Atoll, US** No Stress Current DHW 0.0 Hist Max DHW 4.6(1987) Current SST(C) 21.6 Max Month SST 26.9	**Guam** No Stress Current DHW 0.0 Hist Max DHW 5.1(1999) Current SST(C) 27.7 Max Month SST 29.5	**Oman-Muscat** No Stress Current DHW 0.0 Hist Max DHW 16.7(2012) Current SST(C) 23.5 Max Month SST 30.3
Sombrero Reef, FL No Stress Current DHW 0.0 Hist Max DHW 13.6(2011) Current SST(C) 23.5 Max Month SST 29.3	**Oahu-Maui, HI** No Stress Current DHW 0.0 Hist Max DHW 7.6(1996) Current SST(C) 23.9 Max Month SST 27.0	**Enewetok** No Stress Current DHW 0.0 Hist Max DHW 2.5(2001) Current SST(C) 27.6 Max Month SST 29.1	**Maldives-Male** No Stress Current DHW 0.0 Hist Max DHW 10.5(1998) Current SST(C) 28.5 Max Month SST 29.9
Bahamas, Lee Stocking Is No Stress Current DHW 0.0 Hist Max DHW 7.8(1998) Current SST(C) 25.9 Max Month SST 29.3	**Palmyra, Isl** No Stress Current DHW 0.0 Hist Max DHW 9.1(2009) Current SST(C) 27.4 Max Month SST 28.7	**Palau** No Stress Current DHW 0.0 Hist Max DHW 10.4(1998) Current SST(C) 28.7 Max Month SST 29.5	**Seychelles-Mahe** No Stress Current DHW 0.0 Hist Max DHW 5.9(2010) Current SST(C) 29.1 Max Month SST 29.5
Puerto Rico No Stress Current DHW 0.0 Hist Max DHW 7.6(2005) Current SST(C) 26.3 Max Month SST 28.5	**Galapagos** Bleaching Watch Current DHW 0.0 Hist Max DHW 34.4(1998) Current SST(C) 27.2 Max Month SST 26.5	**Davies Reef** Bleaching Watch Current DHW 1.1 Hist Max DHW 4.8(1987) Current SST(C) 28.7 Max Month SST 28.5	**Cobourg Park** Bleaching Watch Current DHW 0.0 Hist Max DHW 6.0(2010) Current SST(C) 30.7 Max Month SST 29.9
Virgin Islands, US No Stress Current DHW 0.0 Hist Max DHW 10.3(2005) Current SST(C) 25.9 Max Month SST 28.5	**American Samoa-Ofu** Bleaching Watch Current DHW 0.0 Hist Max DHW 7.4(1991) Current SST(C) 29.5 Max Month SST 29.3	**Heron Island** No Stress Current DHW 0.0 Hist Max DHW 6.0(1987) Current SST(C) 27.0 Max Month SST 27.3	**Scott Reef** No Stress Current DHW 5.5 Hist Max DHW 13.3(1998) Current SST(C) 29.4 Max Month SST 30.1
Glovers, Belize No Stress Current DHW 0.0 Hist Max DHW 9.7(1998) Current SST(C) 27.2 Max Month SST 28.9	**Tahiti-Moorea** No Stress Current DHW 0.0 Hist Max DHW 7.3(1991) Current SST(C) 28.3 Max Month SST 28.8	**Fiji-Beqa** Bleaching Watch Current DHW 2.5 Hist Max DHW 7.9(2006) Current SST(C) 28.8 Max Month SST 28.1	**Ningaloo, AU** Bleaching Alert Level 2 Current DHW 9.1 Hist Max DHW 11.3(1999) Current SST(C) 30.0 Max Month SST 28.2

Figure 8. Webpage of CRW's 24 operational Virtual Stations for March 4, 2013.

When thermal stress at the Bleaching Watch level is present at a Virtual Station, a small red triangular warning icon appears next to that Virtual Station on the webpage, and the thermal stress level is displayed in red text (Fig. 8). A larger red triangular icon is displayed when a Bleaching Warning is posted. At Bleaching Alert Level 1, the stress level is displayed in bold red text. Once the user is familiar with this system, it is easy to understand thermal stress levels by glancing at the Virtual Stations table.

Since DHW is a 12-week accumulation of HotSpots, it is possible for a location to have a non-zero DHW value when the HotSpot value is less than 1 °C or even 0 °C. Hence, at a status level of "No Stress" or "Bleaching Watch," it is possible for the corresponding DHW value to be greater than 0 °C-week. This condition simply means that there has been thermal stress at that location within the last 12 weeks, but local conditions are not currently stressful for corals. Previous thermal stress exposure may still have adverse impact on the corals, although recovery may be underway.

To help the user understand the temporal context of current stress-level indicators, time series graphs and data of SST, SST Anomaly, HotSpots, and DHW are provided for each of the 24 operational Virtual Stations (see Section 2.10 for details). We also provide automatic e-mail alerts for these sites; users can subscribe to the e-mail alerts for free at our subscription page (see Section 2.11 for details).

2.9.2 Experimental Virtual Stations

In addition to the 24 operational Virtual Stations described above, CRW has 227 experimental Virtual Stations, released in March 2011, which will become operational in March 2013.

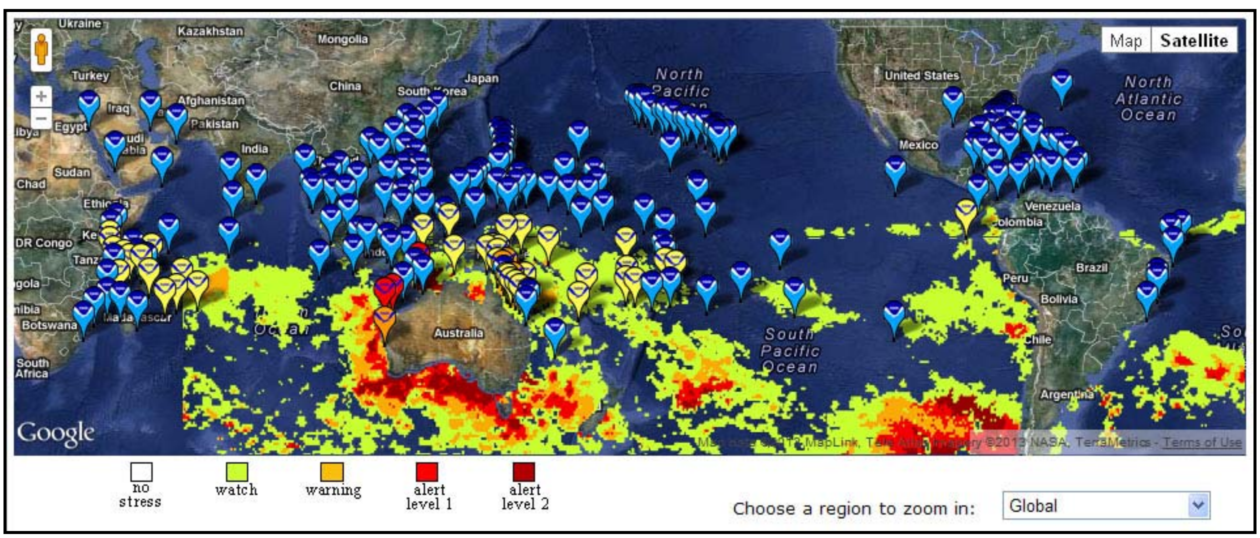

Figure 9. Google Map display of CRW's 24 operational and 227 experimental Virtual Stations for March 4, 2013 with the Bleaching Alert Area image of the same date in the background.

Access to experimental Virtual Stations is through CRW's Google Maps interface, http://coralreefwatch.noaa.gov/satellite/vs/index.html (Fig. 9), where station markers are color-coded using the same color scheme as the Bleaching Alert Area product (Fig. 5), to show current alert status. Users can click on a station to see current thermal stress conditions (i.e., present coral bleaching thermal stress level, SST, SST Anomaly, HotSpot, and DHW values) and to link to time series graphs and data. An alternate text-based webpage (http://coralreefwatch.noaa.gov/satellite/vs/docs/list_vs_group_latlon_201103.html) provides access to the same information for users who prefer a simpler interface. CRW also provides automatic e-mail alerts for all 227 experimental sites (described in Section 2.11).

CRW will continue to add experimental Virtual Stations to its website based on user requests. New stations are integrated into the existing operational and experimental Virtual Stations system and Google Maps interface on a non-regular basis. In the interim, current thermal stress conditions and links to time series graphs and data for recently requested stations are available from an "Additional Experimental Stations" webpage: http://coralreefwatch.noaa.gov/satellite/vs_added/vs_wa_list_data.html, accessible from the main Virtual Stations webpage (see link above).

2.10 Time Series Graphs and Data for Virtual Stations

CRW's time series graphs display the twice-weekly 50 km satellite SST, HotSpots, DHW, and coral bleaching thermal stress level (Table 1) at the 24 operational and 227 experimental Virtual Stations for the period 2000-present. Currently, two types of graphs are available: two-year graphs (Fig. 10) and multi-year graphs (Fig. 11). Graphs for CRW's operational Virtual Stations are available at: http://www.osdpd.noaa.gov/ml/ocean/cb/sst_series_24reefs.html, and graphs for the experimental Virtual Stations can be found at: http://coralreefwatch.noaa.gov/satellite/vs/docs/list_vs_group_latlon_201103.html (both accessible via the CRW website).

Both graph types are created from the same operational twice-weekly 50 km product suite data that are used to update the Virtual Stations product. Graphs and corresponding data depict both the historical record and current condition of SST and thermal stress at each Virtual Station. Note that time series data from 2000 are available for only part of December and are plotted only in the 2000-2001 two-year graphs; they are not plotted in any multi-year graph (Fig. 11).

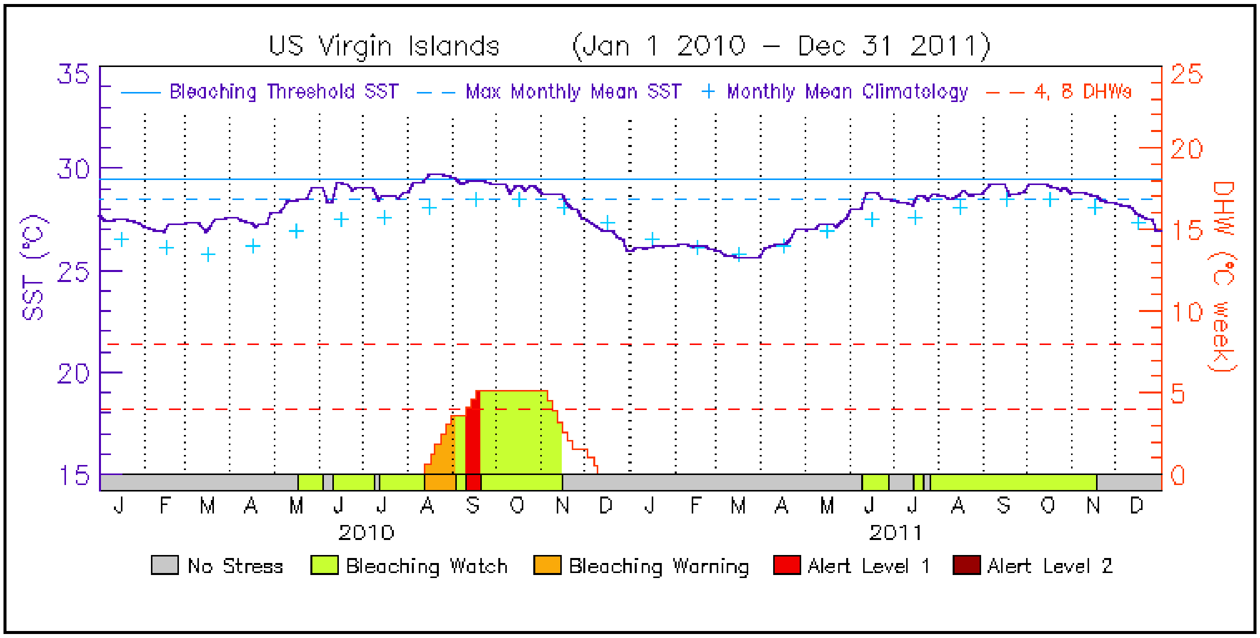

Figure 10. CRW's 2010-2011 two-year time series graph for the Virtual Station at U.S. Virgin Islands (satellite pixel location between St. Croix and St. John).

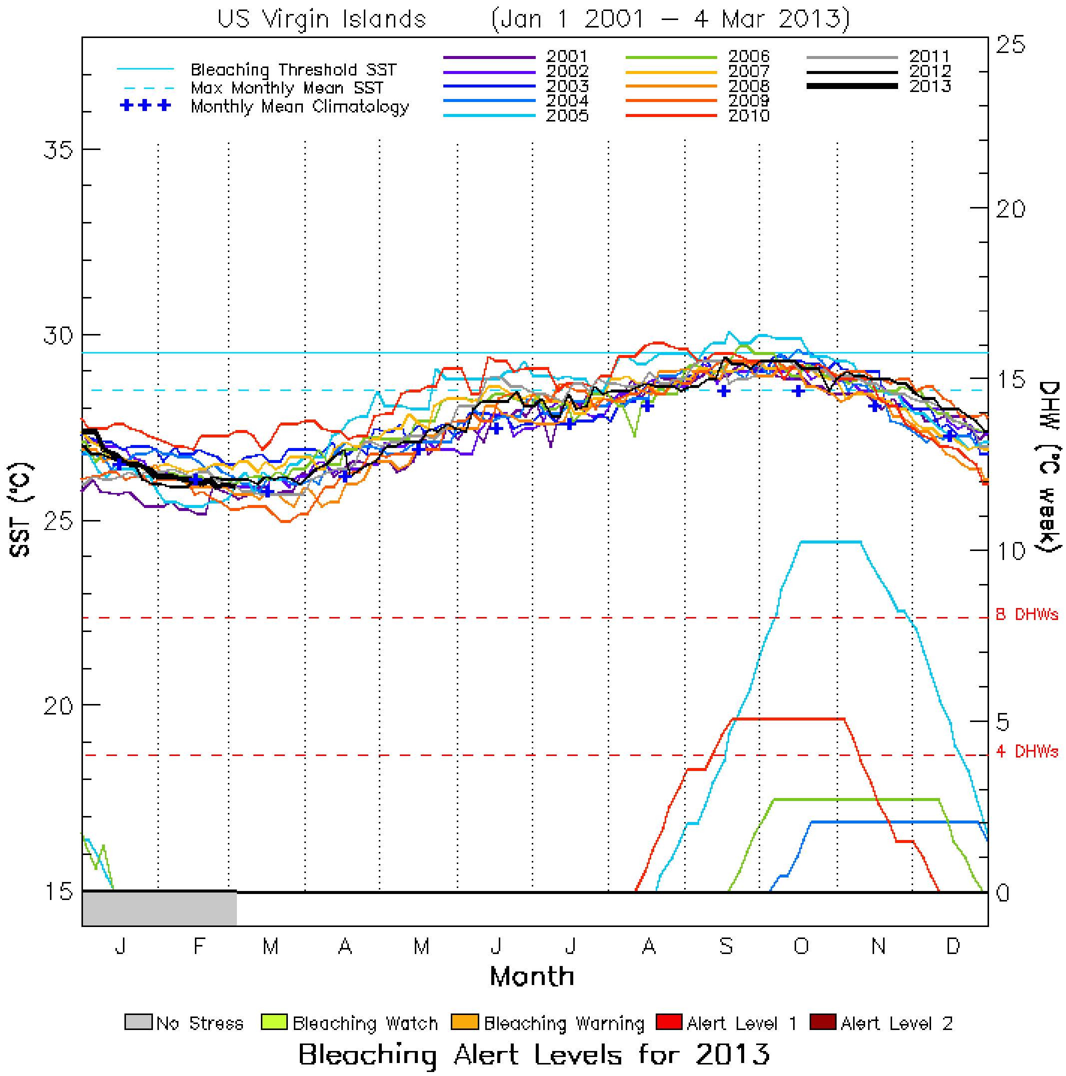

Figure 11. CRW's 2001-2013 multi-year time series graph for the Virtual Station at U.S. Virgin Islands (satellite pixel location between St. Croix and St. John).

In both graph types, SST is plotted referencing the left vertical axis. The temperature scale is consistent across all Virtual Stations, incorporating the range of temperatures experienced at coral reef locations globally. DHW is plotted in the bottom portion of the graph and read using the right vertical axis. Red dashed lines across the graphs indicate DHW threshold values of 4- and 8 °C-weeks (triggers for Bleaching Alert Levels 1 and 2, respectively). In the multi-year graph (Fig. 11), SST and DHW time series for the current year are plotted as a thick black solid line; the time series from the previous two years are plotted in thin black and gray lines to make them distinguishable from earlier years.

The coral bleaching thermal stress level (Table 1) is color-coded using the same color scheme as the Bleaching Alert Area product (Fig. 5) and plotted along the lower horizontal axis. On the multi-year graph (Fig. 11), the coral bleaching thermal stress level reflects the current year.

Three pieces of information describing the long-term mean conditions at a Virtual Station are provided on the two-year and multi-year graphs: the 12 monthly mean SST climatologies, the

MMM SST climatology, and the bleaching threshold SST (defined as MMM+1 °C). The 12 monthly mean SST climatologies (blue crosses) are plotted to show average SST conditions at each Station throughout the year; the peak of the bleaching season typically falls during or immediately following the warmest months of the climatology. The time of peak bleaching varies among ocean basins and hemispheres. Generally, for the northern Atlantic Ocean and northern Pacific Ocean, it is July-September; for the southern Atlantic Ocean and southern Pacific Ocean, January-March. The peak season for the northern Indian Ocean is April-June and for the southern Indian Ocean, January-April. Near the equator there are often two potential bleaching "seasons."

The MMM SST climatology is featured as a dashed light-blue line on the graphs. The coral bleaching threshold SST is plotted as a solid light-blue line at 1 °C above the MMM SST line. The monthly mean SST climatology, MMM SST, and Coral Bleaching Threshold SST are static for and specific to each location.

Multi-year graphs provide a convenient way for managers and scientists to compare time series data among years, while recent thermal conditions can be examined easily on the two-year graphs. For example, the accumulated thermal stress (DHW) at the U.S. Virgin Islands Virtual Station (Fig. 10) reached Bleaching Alert Level 1 during 2010, indicating the presence of thermal stress sufficient to cause significant bleaching. The corresponding multi-year graph (Fig. 11) shows that there has been only one additional severe thermal stress event at this location (in 2005), which exceeded the level at which significant mortality was expected. A comprehensive description of the graphs is available at: http://coralreefwatch.noaa.gov/satellite/data_nrt/descriptions/description_vs_graphs.html.

Time series data of CRW's SST, SST Anomaly, HotSpots, and DHW products for the Virtual Stations, from December 2000-present, are available in ASCII text (Fig. 12) for both the operational and experimental Virtual Stations at: http://coralreefwatch.noaa.gov/satellite/current/products_vs.html. A detailed description of the time series data is also available at: http://coralreefwatch.noaa.gov/satellite/data_nrt/descriptions/timeseries.txt.

BYYY	BM	BD	BH	EYYY	EM	ED	EH	SST	SSTANOM	HOTSPOT	DHW	Lat	Lon	Reef_Name
2010	07	01	04	2010	07	05	03	29.10	1.53	0.60	0.00	18.0	-65.0	US Virgin Islands
2010	07	05	03	2010	07	08	04	29.10	1.52	0.60	0.00	18.0	-65.0	US Virgin Islands
2010	07	08	04	2010	07	12	04	28.50	0.91	0.00	0.00	18.0	-65.0	US Virgin Islands
2010	07	12	04	2010	07	15	03	28.70	1.10	0.20	0.00	18.0	-65.0	US Virgin Islands
2010	07	15	03	2010	07	19	04	28.70	1.04	0.20	0.00	18.0	-65.0	US Virgin Islands
2010	07	19	04	2010	07	22	03	28.70	0.99	0.20	0.00	18.0	-65.0	US Virgin Islands
2010	07	22	03	2010	07	26	03	28.60	0.82	0.10	0.00	18.0	-65.0	US Virgin Islands
2010	07	26	03	2010	07	29	04	28.90	1.07	0.40	0.00	18.0	-65.0	US Virgin Islands
2010	07	29	04	2010	08	02	03	28.90	1.01	0.40	0.00	18.0	-65.0	US Virgin Islands
2010	08	02	03	2010	08	05	04	29.40	1.46	0.90	0.00	18.0	-65.0	US Virgin Islands
2010	08	05	04	2010	08	09	04	29.40	1.40	0.90	0.00	18.0	-65.0	US Virgin Islands
2010	08	09	04	2010	08	12	03	29.40	1.35	0.90	0.00	18.0	-65.0	US Virgin Islands
2010	08	12	03	2010	08	16	05	29.70	1.59	1.20	0.60	18.0	-65.0	US Virgin Islands
2010	08	16	05	2010	08	19	04	29.80	1.65	1.30	1.25	18.0	-65.0	US Virgin Islands
2010	08	19	04	2010	08	23	03	29.80	1.60	1.30	1.90	18.0	-65.0	US Virgin Islands
2010	08	23	03	2010	08	26	05	29.70	1.46	1.20	2.50	18.0	-65.0	US Virgin Islands
2010	08	26	05	2010	08	30	03	29.60	1.31	1.10	3.05	18.0	-65.0	US Virgin Islands
2010	08	30	03	2010	09	02	03	29.60	1.27	1.10	3.60	18.0	-65.0	US Virgin Islands
2010	09	02	03	2010	09	06	05	29.30	0.92	0.80	3.60	18.0	-65.0	US Virgin Islands
2010	09	06	05	2010	09	09	03	29.30	0.88	0.80	3.60	18.0	-65.0	US Virgin Islands
2010	09	09	03	2010	09	13	05	29.50	1.03	1.00	4.10	18.0	-65.0	US Virgin Islands
2010	09	13	05	2010	09	16	05	29.50	1.00	1.00	4.60	18.0	-65.0	US Virgin Islands
2010	09	16	05	2010	09	20	03	29.50	1.00	1.00	5.10	18.0	-65.0	US Virgin Islands
2010	09	20	03	2010	09	23	05	29.40	0.90	0.90	5.10	18.0	-65.0	US Virgin Islands
2010	09	23	05	2010	09	27	03	29.30	0.80	0.80	5.10	18.0	-65.0	US Virgin Islands
2010	09	27	03	2010	09	30	03	29.30	0.80	0.80	5.10	18.0	-65.0	US Virgin Islands
2010	09	30	03	2010	10	04	05	29.30	0.80	0.80	5.10	18.0	-65.0	US Virgin Islands
2010	10	04	05	2010	10	07	03	29.30	0.80	0.80	5.10	18.0	-65.0	US Virgin Islands
2010	10	07	03	2010	10	11	03	28.80	0.30	0.30	5.10	18.0	-65.0	US Virgin Islands
2010	10	11	03	2010	10	14	05	29.10	0.60	0.60	5.10	18.0	-65.0	US Virgin Islands
2010	10	14	05	2010	10	18	03	29.20	0.74	0.70	5.10	18.0	-65.0	US Virgin Islands
2010	10	18	03	2010	10	21	03	29.00	0.58	0.50	5.10	18.0	-65.0	US Virgin Islands
2010	10	21	03	2010	10	25	05	29.20	0.83	0.70	5.10	18.0	-65.0	US Virgin Islands
2010	10	25	05	2010	10	28	03	29.10	0.77	0.60	5.10	18.0	-65.0	US Virgin Islands

Figure 12. Excerpt of CRW's 2000-present time series data for the Virtual Station at U.S. Virgin Islands (satellite pixel location between St. Croix and St. John).

The first row of each time series data file, the header, provides the title for each of the 15 fields in the record, described in detail below. Each subsequent row provides data for one twice-weekly composite period.

BYYY, BM, BD, BH (beginning time): These are the year, month, day, and hour (UTC), respectively, that begin the twice-weekly composite time period of a record, showing the hour of the first satellite measurement processed for the record. Only nighttime SST observations are used for coral bleaching monitoring. The POES orbit period, which is the time it takes the satellite to complete one orbit of the Earth, is approximately 100 minutes. The change of the product update time from Tuesday and Saturday mornings to Monday and Thursday mornings on May 3, 2007 is identifiable in the date of the time series data records.

EYYY, EM, ED, EH (ending time): These are the year, month, day, and hour (UTC), respectively, of the most recent nighttime SST measurement processed for the record. In a time series, if a composite's ending time (EYYY, EM, ED, EH) is much later than the usual ending time associated with its scheduled product processing time or is out of the pattern of most ending times in the series, a technical interruption might have occurred at the time of data processing; processing then resumed at a later time and included any additional observations available at that time. The beginning time and ending time together define the time period for a twice-weekly composite. During a successful twice-weekly data update, the BYYY, BM, BD, and BH are identical to the EYYY, EM, ED, and EH, respectively, of the previous record. In the time series, any existing gap between the beginning time (BYYY, BM, BD, BH) of a composite record and the end time (EYYY, EM, ED, EH) of the previous record indicates missing data during the gap. The cause of missing data, which are infrequent, varies, such as failure to acquire source satellite observations or interruption in routine data processing due to computer breakdowns.

SST, SSTANOM, HOTSPOT, and DHW: These are the twice-weekly SST (°C), SST Anomaly (°C), Coral Bleaching HotSpot (°C), and DHW (°C-weeks) values at the corresponding Virtual Station (50 km pixels).

Lat and Lon: These are the latitude and longitude of the center of the pixel in units of degrees-north and degrees-east, respectively.

Reef_Name: This is the name of the reef site for which the Virtual Station provides information.

The Virtual Stations time series graphs and data integrate and deliver the most comprehensive site-specific information available from the CRW coral bleaching thermal stress monitoring product suite. Released experimentally on the CRW website in April 2001 and June 2007, respectively, they were promoted to operational status in November 2011.

2.11 Automated Satellite Bleaching Alert (SBA) E-mails

CRW's Satellite Bleaching Alert (SBA) system is an automated, free e-mail system that monitors and alerts users to thermal stress conducive to coral bleaching, as detected by CRW's global satellite near-real-time monitoring products. It automatically delivers up-to-date information on changing Bleaching Alert status of local coral reef environments to reef managers, scientists, and other stakeholders. The SBA was launched in July 2005 as a companion operational product for the 24 operational Virtual Stations. Currently, the automated email alert is available for the 227 experimental Virtual Stations as well. A sample experimental SBA message is shown in Fig. 13.

```
[NOAA Coral Reef Watch Coral Bleaching Alert 20121022]
              (Experimental product)

Atlantic Ocean

** Caribbean
        -- Bocas del Toro, Panama              (+) Bleaching Watch
        -- Guadeloupe                          (-) Bleaching Watch
        -- Lee Stocking Island, Bahamas        (+) Bleaching Watch
        -- Los Roques, Venezuela               (+) Bleaching Warning
        -- Turks and Caicos                    (+) Bleaching Warning

Pacific Ocean

** Micronesia

   == Federated States of Micronesia
        -- Pisaras, FSM                        (-) No Stress
        -- Pulusuk, FSM                        (+) Bleaching Watch

   == Other Micronesia Stations
        -- Phoenix Islands, Kiribati           (+) Bleaching Watch
        -- Tarawa, Kiribati                    (+) Bleaching Warning

** TOGA_TAO
        -- TOGA-TAO 5n147e                     (+) Bleaching Watch

 (+) and (-): indicating increase or decrease in bleaching thermal stress level at a
              station from its previous stress level.
```

Figure 13. Sample summary section of an automated CRW Satellite Bleaching Alert e-mail message. Detailed thermal stress information (not shown) for each affected Virtual Station is included in the e-mail message.

An automated e-mail is sent to a subscriber when the level of coral bleaching thermal stress changes (Table 1) and/or when a new thermal stress record is set at the Virtual Stations to which the user subscribes. The thermal stress status is evaluated twice-weekly. All information normally found on the Virtual Stations webpage (http://coralreefwatch.noaa.gov/satellite/current/products_vs.html) is included in the SBA emails, as well as internet links to time series graphs and global/regional images, and previous bleaching alert levels experienced at the affected Station.

The SBA is a convenient data delivery system that allows critical information about coral bleaching thermal stress to reach a user's (manager, researcher, etc.) desktop immediately, without the user having to manually check the CRW website for updated information.

To receive automated e-mail alerts for any of the 24 operational Virtual Stations, visit: http://coralreefwatch-satops.noaa.gov/SBA.html; from this page, a user can also view and alter selection(s) or unsubscribe from the e-mail list. To receive automated e-mail alerts for experimental Virtual Stations, send an e-mail to coralreefwatch@noaa.gov and include the Station(s) to which you would like to subscribe.

2.12 CRW Thermal Stress Satellite Monitoring Source Data

Source data for most CRW products have been available on the CRW website at: http://coralreefwatch.noaa.gov/satellite/hdf/index.html, for free download and use, since April

2006. These data (2000-present) can be accessed in the Hierarchical Data Format (HDF) via FTP, HTTP, OPeNDAP, and THREDDS servers. Preview images (graphic displays) of the data are also provided.

CRW also provides a free NOAA software tool, the CoastWatch Data and Analysis Tool (http://coastwatch.noaa.gov/cwn/cw_software.html), for visualizing data, viewing data information and values, calculating certain statistics, creating graphical output, and more. Instructions on installing and using the tool are provided at: http://coralreefwatch.noaa.gov/satellite/hdf/index.html. The tool is customized for CRW's HDF data files but is not required to visualize and manipulate CRW's HDF data; many commonly used computer languages and software packages can read and process HDF files.

2.13 CRW Products in Google Earth Format

The majority of CRW's near-real-time satellite global environmental monitoring products are produced in Google Earth format (Fig. 14). Some archived products and products developed for special projects (e.g., specific bleaching events) are also available via Google Earth. Users can easily display CRW products in Google Earth by visiting: http://coralreefwatch.noaa.gov/satellite/ge/index.html. No software installation is required (except for downloading the free version of Google Earth at earth.google.com). Once the link is added to "My Place" in Google Earth on a user's computer, CRW's products can be launched thereafter, directly from Google Earth. For CRW's online-version of Google Earth products, internet access is required to display images. For offline-version products, users can download complete packages containing Google Earth program files and images (i.e., kmz files) and display the products without a live internet connection. Detailed instructions are provided on CRW's Google Earth webpage. CRW's Google Earth product package became available on the CRW website in April 2006 as one of the very first Google Earth products from NOAA. Many new layers and products have been added since then. Additionally, CRW's Google Earth product suite is now featured in Google Earth's Earth Gallery, within the Science and Environment category, at: http://www.google.com/gadgets/directory?synd=earth&hl=en&cat=science_environment&id=1032735918940&start=96. Many teachers have found this package useful in the classroom.

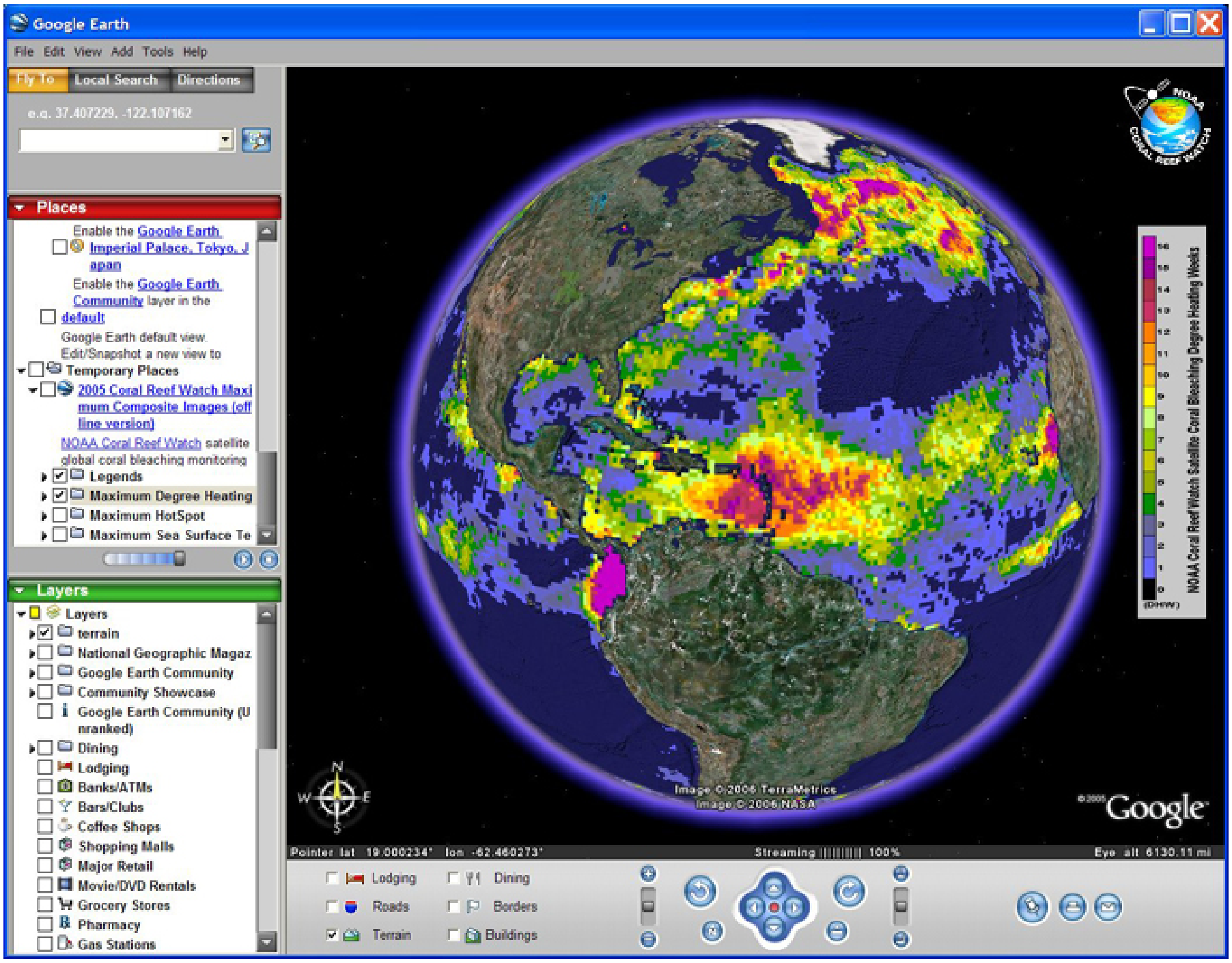

Figure 14. Google Earth display of the maximum composite of CRW's 50 km satellite Coral Bleaching Degree Heating Weeks (DHW) during the 2005 record-breaking mass coral bleaching event in the Caribbean.

2.14 CRW Products in the ReefBase Online GIS System

Through a long-term collaboration with the ReefBase project, administered by WorldFish (a member of the Consultative Group on International Agriculture Research [CGIAR]), monthly and annual composites of CRW's twice-weekly 50 km satellite coral bleaching thermal stress products have been incorporated into ReefBase's Online Geographic Information System (ReefGIS) since September 2003. This online GIS system (www.reefbase.org) allows users to display coral reef related data and information on interactive maps. Users can zoom, search and query data layers and save and bookmark the map. CRW's 24 operational Virtual Stations were added into ReefGIS when the latest version of ReefGIS was released in June 2007. Fig. 15 shows a screenshot of ReefGIS displaying CRW's DHW data layer.

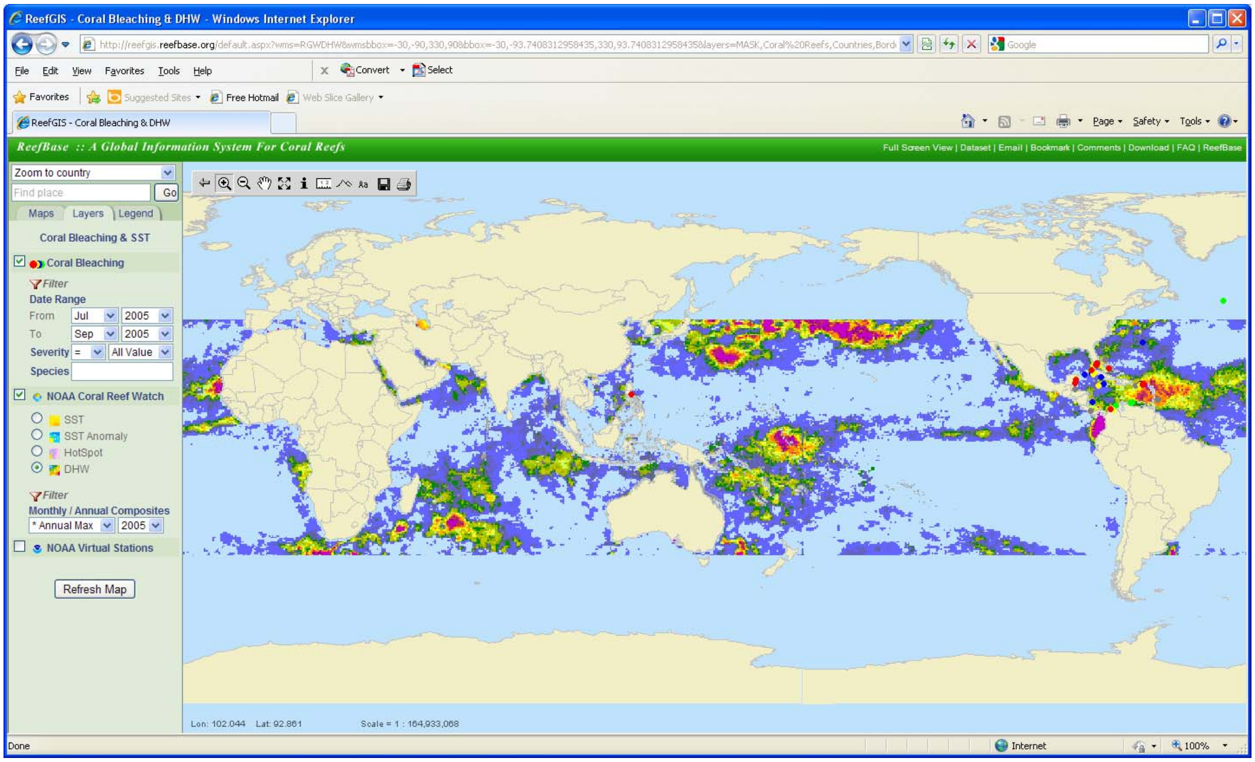

Figure 15. ReefGIS display of the 2005 annual maximum composite of CRW's twice-weekly 50 km satellite coral bleaching Degree Heating Weeks (DHW).

2.15 Tutorial for Coral Reef Watch Products

A tutorial covering CRW products has been developed to provide background information on satellite remote sensing, coral bleaching, and more. Written for both the coral reef management community and the general public, the tutorial can be accessed at: http://coralreefwatch.noaa.gov/satellite/education/tutorial/crw15_intro_products.html.

2.16 Enhanced 50 km (E-50) Product Suite

In 2009, CRW developed and implemented a suite of "enhanced" twice-weekly 50 km satellite coral bleaching monitoring products (or E-50 products) that provide two major improvements over the operational 50 km product suite.

The first major improvement provided coverage for areas closer to the coastlines. The land mask used in CRW's operational 50 km products defines almost all of the 50 km pixels that contain both land mass and sea as land pixels. While this land mask, developed in the early years of satellite SST remote sensing, significantly reduces potential contamination from satellite-measured land surface temperature in producing the 50 km SST analysis for these pixels, it also discards valid satellite SST measurements within coastal pixels, which is where most coral reefs exist. As a result, the current operational land mask enables direct monitoring of only 40% of the world's coral reefs (Fig. 16a and Fig. 17a). For the other 60% of reefs, thermal stress values are usually obtained from offshore waters adjacent to coral reef areas. During most mass coral bleaching events, temperature anomalies usually occur in phase or nearly in phase over a broad area that includes both reefs and adjacent open ocean waters. This allows the CRW operational 50 km products to work well in detecting mass coral bleaching events caused by large-scale thermal stresses. However, coastal water temperatures over reefs can exceed those seen in adjacent offshore pixels and may have much greater lateral temperature gradients, dramatically different vertical profiles, and much shorter temporal scales. As a result, the CRW operational products may underestimate smaller (local) thermal stress events and miss small-scale features and high frequency variations found in and around the reefs that are obscured by the operational land mask.

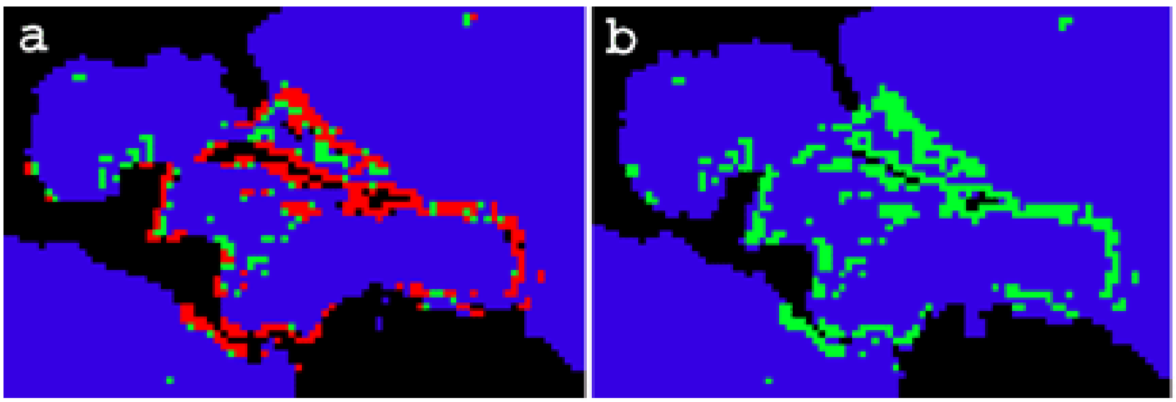

Figure 16. Comparison of CRW's (a) operational 50 km land mask and (b) enhanced 50 km (E-50) land mask for the Caribbean and surrounding regions. Black pixels: land pixels (no data provided); Blue pixels: water pixels (i.e., data pixels); Red pixels: pixels masked as land containing coral reefs (no data provided); Green pixels: water pixels containing coral reefs.

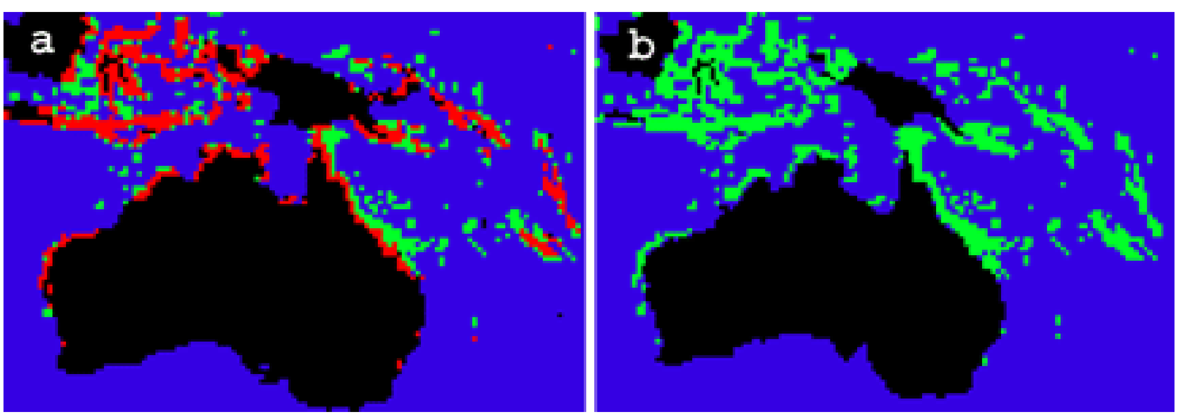

Figure 17. Comparison of CRW's (a) operational 50 km land mask and (b) enhanced 50 km (E-50) land mask for Australia and surrounding regions. Black pixels: land pixels (no data provided); Blue pixels: water pixels (i.e., data pixels); Red pixels: pixels masked as land containing coral reefs (no data provided); Green pixels: water pixels containing coral reefs.

To create a new land mask with improved spatial coverage for monitoring coral reef areas, CRW used the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at a spatial resolution of 30 arc-seconds (approximately 1 km at the equator) to more accurately identify ocean-containing 50 km coastal pixels excluded from the operational products by the operational land mask. A SRTM-based 50 km (0.5 degree) land mask with the same grid layout as the current operational 50 km products was developed and implemented in the E-50 product suite. This new 50 km land mask treats all pixels that include both land and sea as water pixels and allows the use of the original 4 km AVHRR GAC SST retrievals from the water portion of these pixels (Fig. 16b and Fig. 17b). In this way, the E-50 greatly improves monitoring capacity into coastal waters by providing thermal stress monitoring for more than 99% of the 50 km pixels containing coral reefs globally, as compared to 40% with the operational 50 km product suite. The UNESCO database of global reef locations, accessible via ReefBase (www.reefbase.org) was used to identify reef-containing satellite pixels.

The second major improvement is the development of a new climatology. CRW's SST Anomaly, Coral Bleaching HotSpots, and DHW are derived by comparing current temperatures to climatological values. To produce these parameters in the new coastal water pixels, new 50 km global monthly mean SSTs and a MMM SST climatology were required. These were produced from a 50 km, twice-weekly SST dataset that was derived from high-quality reprocessed Version 5.0 Pathfinder 4 km AVHRR satellite SST data (Eakin et al., 2009). The Pathfinder-based 50 km SST was compared with the E-50 SST to ensure equivalence and this showed a strong linear relationship with only a small offset. This linear relationship was later applied to adjust the Pathfinder-based SST climatologies for near-real-time use with the E-50 SST. The new climatology improved overall accuracy of the E-50 products and addressed several known errors in CRW's original operational climatology that had caused overly-high SST Anomaly and HotSpot values for the area around the Gulf of Panama, in the Gulf of Oman, and in some high latitude regions. Furthermore, the new climatology was derived based on the entire 1985-2006 time series (22 years) of the Version 5.0 Pathfinder 4 km AVHRR SST available at the time of development, as compared with the reduced time period (7 years: 1985-1993, excluding 1991 and 1992; see Section 2.2) used to produce the operational climatology. However, analysis of long-term temperature trends over the 22-year dataset (Eakin et al., 2009) indicated that warming had occurred during this period at the studied coral reef locations. To maintain the interpretation of the CRW products (i.e., the described DHW thresholds for ecological impact, Section 2.5), the observed long-term temperature trends were used to adjust the time-center of the 22-year monthly mean values to that of the 7-year time period. Finally, the linear relationship between the E-50 and Pathfinder-derived 50 km SST values was applied to the new climatologies to ensure they were directly compatible with the E-50 SST.

A sample composite DHW image for the Caribbean, which revealed high-resolution coastlines when the E-50 land mask was applied (Fig. 18a), demonstrates increased coastal coverage as compared to the same composite DHW image filtered by the current operational 50 km land mask (Fig. 18b).

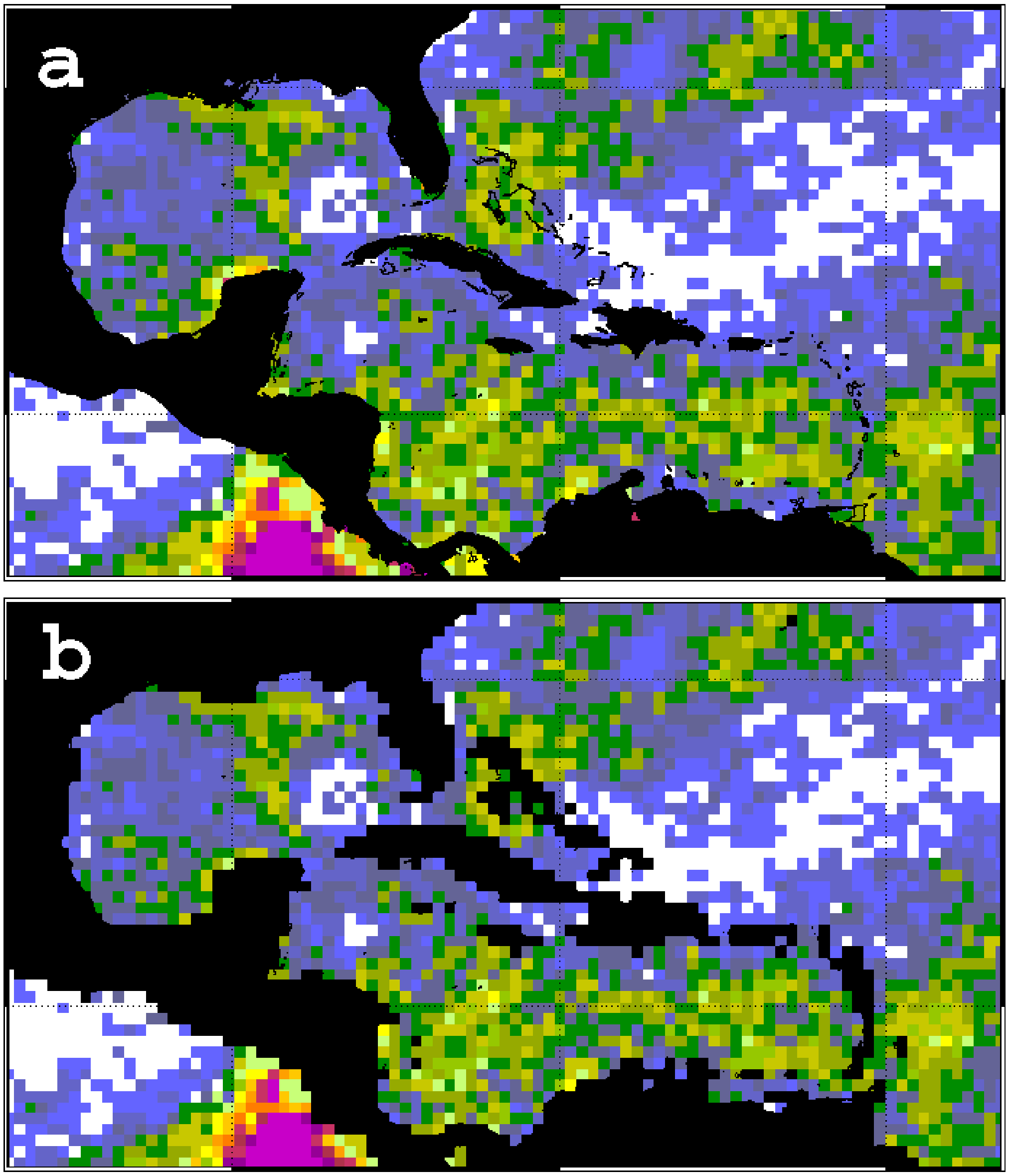

Figure 18. Comparison of CRW's (a) enhanced 50 km (E-50) land mask and (b) operational 50 km land mask for the Caribbean on a sample composite Degree Heating Weeks image.

Differences exist between the experimental E-50 and operational product suites in certain areas, mainly due to the new climatology being used in the E-50, and user discretion is advised. The expectation is that the E-50 products are more accurate in general, especially in the regions around the Gulf of Panama and Gulf of Oman. Users in Southeast Asia have indicated that the E-50 product shows a significant improvement in that region (N. Setiasih, pers comm).

The E-50 product suite was launched in 2009 on the CRW website (http://coralreefwatch.noaa.gov/satellite/e50/index.html) and continues to run alongside the operational 50 km product suite. The E-50 products are updated twice-weekly on the same days as the operational products.

2.17 Contingency 50 km Product Suite

A contingency plan, in case of dramatic failure, may be considered a component of an effective operational system. In 2011, CRW began developing a contingency 50 km product suite to address this potential need and ensure continuity of product delivery to global users. With the development and availability of new high-resolution satellite SST products (see below), the NESDIS plan was to no longer make any major investment in the operational 50 km SST. Any unexpected failure in NOAA's operational polar-orbiting satellite (currently NOAA-19) or major technical malfunction in the computing facilities and software that CRW's operational 50 km products rely on, therefore, would result in the termination of the operational 50 km SST and CRW's 50 km coral bleaching thermal stress monitoring products. CRW employed one of NESDIS' new operational SST products, at 0.1 degree (~11 km) and daily resolution, to produce a 50 km twice-weekly SST product emulating the methodology of CRW's current operational 50 km SST (Section 2.1). Note that the 11 km SST is derived from multiple polar- and geosynchronous-orbit satellites, minimizing the impact of loss of an individual satellite. As the methodology to develop SST climatologies at 50 km resolution already existed for the E-50 product suite, based on the Version 5.0 Pathfinder SST, the procedure followed there was replicated (Section 2.16); i.e., determine the linear relationship between the 50 km Pathfinder-derived SST and the contingency SST datasets, and apply this relationship to the existing time-centered Pathfinder-based 50 km climatologies. Existing work to produce the E-50 product suite substantially reduced the amount of effort required to develop and evaluate the contingency climatologies and product suite, as compared with developing the climatologies and product suite at the native spatial resolution (11 km) of the new SST dataset. Since mid-2012, the contingency 50 km SST data and coral bleaching thermal stress monitoring products (SST Anomaly, Coral Bleaching HotSpots, and DHW) have been routinely produced and would become publicly available only if necessary.

3 Discussions, Conclusions, and Future Directions

NOAA CRW has been operating the world's only global satellite coral bleaching thermal stress monitoring system for the U.S. and international coral reef communities for more than a decade. Over this time period, CRW has evolved from providing a limited number of operational SST-based tools for coral bleaching monitoring, to implementing a decision support system (DSS) monitoring multiple satellite and model-based parameters. While the existing 50 km satellite SST-based products have been successful in monitoring coral reef environmental conditions, continuous improvements are needed, both to adapt to new satellite technologies and to address new environmental threats. CRW is now developing a new-generation, higher-resolution DSS, taking advantage of advances in satellite algorithms for measuring environmental variables, availability of multiple satellites and sensors, model-based evaluations of observations and forecasts, and advances in coral biological and physiological research (Liu et al., 2012). A brief introduction is given below for some of these new products in experimental or research mode; detailed information can be accessed at CRW's website: http://coralreefwatch.noaa.gov/satellite/index.html.

3.1 High-Resolution Bleaching Thermal Stress Monitoring Products

CRW's new, high-resolution global coral bleaching thermal stress monitoring product suite is produced daily at 0.05 degree (~5 km) spatial resolution. The input of this new product suite is NOAA/NESDIS' new operational daily global 5 km SSTs (http://www.ospo.noaa.gov/Products/ocean/sst/contour/index.html and http://www.star.nesdis.noaa.gov/sod/mecb/blended_validation/) generated from measurements taken from multiple geostationary and polar-orbiting satellites operated by NOAA, the Japan Meteorological Agency (JMA), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Note that the methodology used for generating the 5 km SST data was paralleled from the methodology used to produce the 11 km SST dataset employed for CRW's contingency 50 km product suite (Section 2.17); it is anticipated that the contingency products will be transferred to use the 5 km SST data while being maintained as a legacy 50 km product suite. High frequency and high density global ocean coverage, along with significant advances in satellite SST algorithms, ensure dramatic improvements over the heritage twice-weekly 50 km SST used as input in CRW's current operational products. These next-generation SST-based products will continue taking advantage of improvements to the NOAA/NESDIS operational 5 km SST over the next few years to: reduce bias caused by daytime solar heating in the sea surface skin layer; apply physical retrieval algorithms to account for local atmospheric influence; and reduce data loss caused by cloud cover – perhaps through addition of microwave-SST data. The development of a 5 km SST climatology that provides the coral bleaching temperature threshold used in the new bleaching thermal stress monitoring product suite was conducted through a collaboration of CRW, the University of South Florida, NASA-Ames, the UNEP World Conservation Monitoring Centre, and the Cooperative Institute for Research in Environmental Sciences. The high-quality, high-resolution climatology required for this product suite is being developed from the Pathfinder Version 5.2, 4 km AVHRR SST dataset. CRW launched the 5 km product suite in June 2012. As of the preparation of this report, the 5 km product suite used the same HotSpot and DHW algorithms described for CRW's operational 50 km product suite. Given the significant differences in producing NESDIS' operational 50 km and 5 km SST datasets, however, ongoing evaluation of these product algorithms at 5 km resolution may result in changes to improve predictions from the 5 km product suite.

3.2 Light Stress Damage

While mass coral bleaching has generally been predicted well on the basis of excess thermal stress alone, bleaching actually results from the impact of high temperatures on the function of photosystems within a coral's zooxanthellae (Section 1). CRW, in collaboration with the Universidad Nacional Autónoma de México, the University of Queensland, and the University of Exeter, and with support from the Bleaching and Remote Sensing Working Groups of the Coral Reef Targeted Research (CRTR) Program, the Australian Research Council, and the NOAA Coral Reef Conservation Program, is developing the first product to use both satellite-derived light and temperature data to predict photosystem stress that leads to coral bleaching. The methodology uniquely expresses both thermal stress and excess-light stress, as derived from satellite data, as an equivalent light stress value, allowing light and temperature data to be combined. The Light Stress Damage (LSD) product, released for the Greater Caribbean region in October 2012, uses NOAA's daily global 0.1 degree (approximately 11 km spatial resolution) geostationary-polar-orbiting blended satellite SST data (described in Section 2.17) and NOAA's surface solar insolation product from geostationary satellites. The LSD product will be transitioned shortly to use NOAA's daily global 5 km blended satellite SST data and eventually will be expanded into a global product.

3.3 Coral Disease Outbreak Risk

CRW has conducted research in collaboration with various partners to develop a SST-based product that estimates the likelihood of an outbreak of coral disease. The Coral Disease Outbreak Risk is a regional experimental product, currently serving data for the Great Barrier Reef (GBR) and the Hawaiian archipelago. The outbreak risk is assessed using metrics developed for the coldest and warmest times of year. These are combined to provide a Seasonal Outlook metric, issued at the end of the cold season for each region, and a Current Summer Outbreak Risk that is updated in near-real-time during the hot season for each region. Risk assessments are to be interpreted based on local knowledge of coral host density and have been calibrated using White Syndrome observations from the Great Barrier Reef (Heron et al., 2010). While this calibration reflects only one disease group from one region, the product may be useful for broader applications. This new predictive tool will be compared against monitoring data for White Syndrome and with observations of other coral infectious diseases to evaluate the utility of the risk assessment algorithm to various disease types in the GBR and Hawaii. It also will be developed and evaluated for other coral reef regions, with a goal of global coverage. The research collaboration has included, to date, partners from James Cook University, the Australian Institute of Marine Science, the University of Melbourne, Cornell University, NOAA's Coral Reef Ecosystem Division, the Great Barrier Reef Marine Park Authority, and the University of Hawaii.

3.4 Additional Remotely Sensed Environmental Variables

Incorporating additional remotely-sensed environmental variables will provide a more complete prediction of corals' responses to changing environmental conditions and significantly improve the data available to inform coral reef management. A recent analysis by Strong et al. (2012) suggested that Ocean Color (highest priority), Synthetic Aperture Radar (SAR), and Ocean Surface Vector Winds (OSVW) are presently the top non-SST product development areas for application to coral reef environments. Ocean color will directly address land-based sources of pollution (LBSP) and other water quality issues. Surface wind speed and direction provided by SAR and OSVW will contribute toward understanding and monitoring LBSP transportation, oil and chemical spill detection, biological connectivity, climate change resilience via wind generated cooling effects, and possible detection of large-scale spawning events. This analysis provides valuable information for laying potential directions for CRW's long-term product development. The continued development of these new non-SST products will further enhance CRW's DSS by providing valuable information for coral reef management.

4 Acknowledgements

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Council, and many other organizations and individuals, who have contributed to the development of NOAA Coral Reef Watch. The manuscript content solely represents the opinions of the authors and does not constitute a statement of policy, decision, or position on behalf of NOAA or the US Government.

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