Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9-13 July 2012
5A Remote sensing of reef environments

# NOAA Coral Reef Watch's Decision Support System for Coral Reef Management

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

[1]NOAA Coral Reef Watch, E/RA31, 1335 East-West Highway, Silver Spring, Maryland 20910, USA
[2]I.M. Systems Group, 3206 Tower Oaks, Boulevard, Suite 300, Rockville, Maryland 20852, USA
[3]NOAA Coral Reef Watch, 675 Ross River Rd, Townsville, Queensland 4817, Australia
Corresponding author: gang.liu@noaa.gov

**Abstract.** NOAA Coral Reef Watch (CRW) has evolved from providing a limited number of satellite sea surface temperature (SST)-based tools for coral bleaching monitoring, to implementing a decision support system (DSS) monitoring multiple satellite and model-based parameters. CRW is now developing a new-generation 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. This paper provides an introduction and overview of CRW's new-generation, integrated global DSS, utilizing satellite, model, and *in situ* data, both near-real-time and historical, to help managers protect coral reefs in a changing climate.

**Key words:** Satellite Remote Sensing, Coral, Bleaching, Outlook, Coral Reef Watch, Decision Support System.

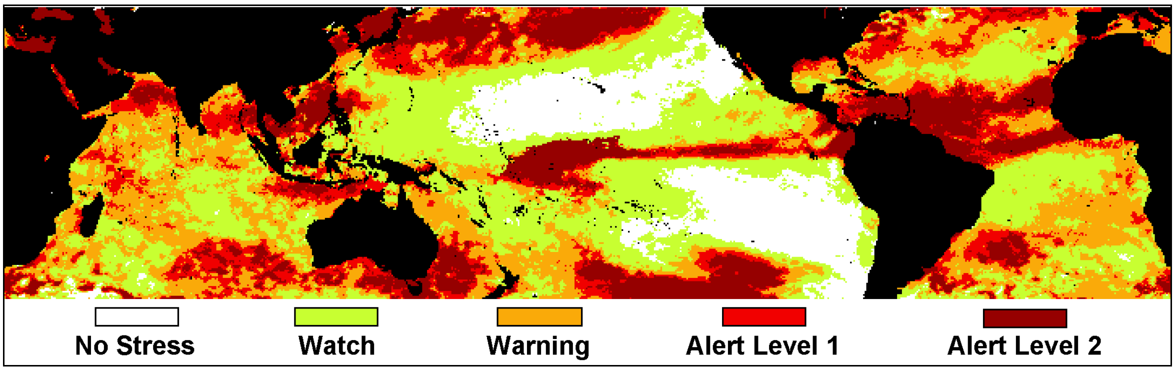


Figure 1. Annual 2010 maximum composite of NOAA Coral Reef Watch's operational twice-weekly 50 km satellite Bleaching Alert Area product, outlining areas where coral bleaching thermal stress met or exceeded predefined bleaching stress levels (Table 1).

## Introduction

Over the past decades, coral reefs have faced unprecedented, dramatic increases in natural and anthropogenic threats, resulting in the rapid decline of many coral habitats worldwide. Established in 2000, the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) program has been utilizing 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 coral reef managers and scientists for accurate and timely information on coral reef ecosystems, CRW has evolved from providing a limited number of satellite sea surface temperature (SST)-based tools, to implementing a web-based global decision support system (DSS) monitoring multiple satellite and model-based parameters.

This paper provides an introduction and overview of CRW's DSS which can be accessed at http://coralreefwatch.noaa.gov. Online tutorials and Liu et al. (2003) demonstrate how to use the DSS. Note that the UNESCO database of global reef locations accessible at ReefBase.org was used to identify reef-containing satellite pixels.

## CRW's Current Decision Support System (DSS)

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). Building on this initial framework, CRW's DSS began to take shape in

2005 when a suite of core satellite coral bleaching monitoring products became operational. Since that time, CRW has continued to expand and upgrade its DSS.

All “50 km” near-real-time SST-based products described in this paper are produced twice-weekly at 0.5° x 0.5° spatial resolution.

*Coral Bleaching HotSpots and SST Anomaly*

CRW’s satellite coral bleaching HotSpots product measures occurrence and magnitude of instantaneous thermal stress potentially conducive to bleaching. It is calculated as the difference between the nighttime SST value and the average nighttime temperature of the warmest month of the year (maximum monthly mean climatology, or MMM) at the same location (Strong et al. 1997; Liu et al. 2003; Skirving et al. 2006b). NOAA’s 50 km ‘gap-filled’ nighttime SST analyses are used for producing the current HotSpots product, which along with the SST and SST Anomaly products, is operational. Nighttime SST is used because it provides more conservative and stable estimates of thermal stress, and compares favorably with *in situ* temperature measurements at one-meter depth (Montgomery and Strong 1994), especially at times when bleaching occurs.

*Coral Bleaching Degree Heating Weeks (DHW)*

Mass coral bleaching is shown to be caused by prolonged periods of thermal stress (Glynn and D'Croz 1990). CRW’s Degree Heating Weeks (DHW) product measures the cumulative impact of thermal stress experienced by corals (Strong et al. 1997). DHW for a given location represents the accumulation of HotSpots of 1 °C or greater at that location over a rolling 12-week period (Liu et al. 2003; Skirving et al. 2006b). Released in 2000, the DHW product has successfully generated bleaching alerts and correlates well with field observations of coral bleaching (Goreau et al. 2000, Wellington et al. 2001; Strong et al. 2002; Liu et al. 2006; Liu et al. 2003; Skirving et al. 2006b; Eakin et al. 2010). When the DHW value reaches 4 °C-weeks, significant bleaching is likely; by the time the DHW value reaches 8 °C-weeks, widespread bleaching is likely and significant mortality can be expected.

*Bleaching Alert Area*

CRW’s Bleaching Alert Area product (Fig. 1) outlines areas where bleaching thermal stress meets or exceeds predefined bleaching stress levels based on CRW’s satellite HotSpot and DHW values (Table 1).

*Virtual Stations*

Virtual Stations are CRW-created stations fully based on CRW satellite products at or near 227 select reef locations worldwide. Using Google Maps and Google Earth interfaces, this product provides near-real-time information from all CRW thermal stress products for each site, as well as time series data and automated e-mail alerts. Virtual Stations are currently set at pre-determined locations; however, users are welcome to request other reef locations. *In situ* data measured in real-time at select long-term monitoring locations at or near some Virtual Stations were also added recently to complement satellite data.

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

Table 1. Stress levels based on current algorithms for producing the CRW coral bleaching HotSpot and Degree Heating Weeks (DHW) products derived from nighttime satellite SST data.

*Automated Satellite Bleaching Alert (SBA) E-mails*

CRW's Satellite Bleaching Alert (SBA) system, available since 2005, is an automated e-mail alert system that delivers critical information for the 227 Virtual Stations directly to subscribers twice-weekly. E-mails are sent when thermal stress levels change at a user’s subscribed stations or a new record is set. To subscribe, go to CRW’s web site or send a request to coralreefwatch@noaa.gov.

*Short-term SST Trends*

SST trends over a given period of weeks provide information on the pace and direction of recent changes in SST and bleaching thermal stress and their potential changes in the immediate future. A 21-day short-term SST trend product based on the latest three weeks of CRW’s twice-weekly satellite SSTs was added to CRW’s DSS in 2009.

*Bleaching Thermal Stress Return Period and Duration Products (Great Barrier Reef)*

Pilot products estimating the return period and duration of thermal stress linked to past mass coral bleaching events became available in 2010 for the Great Barrier Reef (GBR). These products are based on Pathfinder Version 5.0, 4 km AVHRR SST data from 1985-2009. After being evaluated for the GBR, the algorithm will eventually be provided globally. Return period measures the period of time, on average, between repeat occurrences of events reaching three thermal stress levels (DHW>0, ≥ 4, and ≥ 8). The Duration product provides the average length in weeks of thermal stress events at levels DHW≥4 and DHW≥8 for specified GBR sub-regions. Generated using 50 km data, only pixels containing coral reefs are used in the calculations. These two products will be updated about annually as new AVHRR Pathfinder data become available.

*Enhanced 50 km (E-50) Product Suite*

CRW has developed and implemented a suite of "enhanced" twice-weekly 50 km satellite coral bleaching monitoring products (or E-50). The E-50 provides two major improvements over the current operational 50 km product suite. First, the E-50 provides coverage for areas closer to the coast globally. This is achieved through use of the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model at the spatial resolution of 30 arc-seconds (~1 km at the equator) to more accurately identify ocean-containing 50 km coastal pixels that are excluded from the operational products due to the operational land mask. SST is derived only from the over-water regions of these pixels. Although still at the 50 km resolution, the E-50 greatly improves remotely sensed coral reef monitoring capacity 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 product suite. Secondly, an improved climatology was developed for the E-50 by using data from the Pathfinder Version 5.0, 4 km AVHRR SST data set. This climatology improves overall product accuracy and addresses several known errors in the climatology used in CRW's currently operational products described earlier.

The E-50 product suite was launched in 2009 and continues to run alongside CRW's operational 50 km product suite. Differences exist between the two product suites in certain areas globally, 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. CRW expects to discontinue all current 50 km products once transition to the next-generation high-resolution DSS (described below) is complete.

*Statistical Seasonal Bleaching Outlook*

To provide guidance on the likelihood of coral bleaching events months in advance, CRW developed a deterministic, statistical coral bleaching thermal stress outlook system (Liu et al. 2009) based on SST forecasts from a Linear Inverse Modeling (LIM) system (Penland and Matrosova 1998) developed by NOAA's Earth System Research Laboratory (ESRL) for CRW. This outlook system uses a modified version (Liu et al. 2009) of the algorithm used in CRW's satellite coral bleaching thermal stress monitoring to provide weekly bleaching thermal stress outlooks at five potential thermal stress levels matching the stress levels described in Table 1. A summary of the weekly outlooks for the upcoming four months is produced as a seasonal bleaching outlook, and updated weekly. It was released in 2008 as the first global seasonal bleaching outlook product available for coral reef management; Version 2.0 was released in 2010.

*Bleaching Weather Forecast for Florida Keys*

CRW partnered with the NOAA National Weather Service (NWS) forecast office in Key West, Florida to develop a seven-day Bleaching Weather Forecast product that combines wind and cloudiness predictions from the official NWS marine forecast into a short-term risk assessment of weather conditions conducive to coral bleaching. Warm air temperature, low winds, sunny skies, and calm waves are known to induce bleaching events by subjecting corals to high SST and high levels of sunlight (Skirving et al. 2006a). This product, released in 2011, bridges the gap between CRW's near-real-time satellite monitoring and seasonal bleaching outlooks.

*Coral Disease Outbreak Risk Maps*

CRW's Coral Disease Outbreak Risk product estimates the risk of coral disease outbreak and is currently a regional experimental product, released in 2009, serving the GBR and Hawaiian archipelago. Based on CRW's operational twice-weekly 50 km SST, the risk is assessed using metrics developed for the coldest and warmest times of the year (Heron et al. 2010). These are combined to provide a Seasonal Disease Outlook metric, issued at the end of the cold season for each region; and a Coral Disease Outbreak Risk metric, updated in near-real-time during each region's hot season. Risk assessments have been calibrated using White Syndrome observations from the GBR. While this reflects only one disease group from one region, the product may have broader applications. This new predictive tool will be compared against monitoring data for White Syndrome elsewhere and with observations of other infectious coral diseases to determine the applicability of the current algorithm to various disease types and other reef regions.

*Ocean Acidification Product Suite*

CRW's Ocean Acidification Product Suite, released in 2008 (Gledhill et al. 2008), offers a synthesis of satellite and modeled environmental data to provide a synoptic estimate of sea surface carbonate chemistry in the Greater Caribbean region. This tool complements on-going geochemical surveys and monitoring efforts in the region by providing estimates of changing ocean chemistry on broader spatial and temporal scales than shipboard observations alone can permit. The product suite includes monthly averages of aragonite saturation state, carbon dioxide partial pressure, total alkalinity, total $CO_2$, carbonate ion, and bicarbonate ion, derived according to Gledhill et al. (2008). Near-real-time estimates are modeled from daily fields of: NOAA OI AVHRR-AMSRE SST, HYCOM+ NCODA modeled sea surface salinity, NOAA NCEP sea-level pressure, and estimates of atmospheric $CO_2$ derived from the NOAA ESRL GLOBALVIEW-$CO_2$ 2011 reference marine boundary layer (ESRL 2011). The product suite is updated monthly and new data are added as source data become available. Overtime changes have been made to both input data and the algorithm. The latest Version 0.5 was released in 2010.

*Sea Surface Wind Doldrums Product*
CRW developed a global Sea Surface Wind Doldrums product in 2006 to track regions with persistent low wind conditions (doldrums) which can lead to high SST conducive to coral bleaching. Satellite derived wind speeds are obtained by microwave sensors, and the 6-hour wind speed at 10 m height from NOAA/National Climatic Data Center's blended Sea Winds product (Zhang et al. 2006) is used to generate the Doldrums product. In the current product, CRW defines regions of low wind conditions as exhibiting a daily mean of < 3 m/s, based on testing at reefs in Puerto Morelos, Mexico. Duration of the Doldrums condition at each satellite pixel is tracked by accumulating the number of consecutive low wind days. This product is updated daily at 0.25° x 0.25° spatial resolution. While available online, this product undergoes continual development and refinement to determine the best configuration for the algorithm and to test its utility against past bleaching events.

## CRW's New-Generation DSS
CRW is developing a new-generation DSS, taking advantage of advances in satellite algorithms for measuring environmental variables, availability of multiple satellites and sensors, and advances in coral biological and physiological research. The first two products below will be released in June 2012.

*High-Resolution Bleaching Monitoring Products*
CRW's new global coral bleaching monitoring product suite is based on NOAA's new operational daily 5 km global nighttime-only SSTs that are derived from measurements taken by a blend of geostationary and polar-orbiting satellites operated by NOAA, the Japan Meteorological Agency (JMA), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). 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 in CRW's current operational products. The next-generation SST-based products will undergo continuous improvements over the next few years: to reduce bias caused by daytime solar heating in the sea surface skin layer; to apply physical retrieval algorithms to account for local atmospheric influence; and to reduce problems caused by cloud cover – perhaps through addition of microwave-SST data. This development effort is being conducted through collaboration with the University of South Florida, NASA-Ames, the UNEP World Conservation Monitoring Centre, and the Cooperative Institute for Research in Environmental Science. The high-quality, high-resolution climatology required for this product suite was developed from Pathfinder Version 5.2, 4 km AVHRR SST data. CRW's current operational satellite algorithms were re-tuned to include new concepts of coral bleaching thresholds.

*Probabilistic Seasonal Bleaching Outlook*
Through collaboration with NOAA's National Centers for Environmental Prediction (NCEP), CRW developed a probabilistic seasonal coral bleaching thermal stress outlook system based on SSTs from NCEP's operational, real-time Climate Forecast System Version 1 (CFSv1) (Eakin et al. 2012). The CFSv1 is a fully coupled ocean–land–atmosphere dynamical climate prediction system (Saha et al. 2006). CFSv1 produces four SST forecasts daily up to 9 months into the future, and CRW constructs weekly 28-member ensemble of the daily SST forecasts to produce probabilistic HotSpots, DHW, and Bleaching Alert Area outlooks up to four months into the future. Its algorithms were adapted from the LIM-based outlook system (described above and in Liu et al. 2009). Outlooks at 90% and 60% likelihood and probabilistic outlooks for each potential stress level are now available (CRW 2012).

*Light Stress Damage Product (under development)*
While mass coral bleaching is generally predicted on the basis of excess thermal stress alone, bleaching actually results from the impact of high temperatures on the function of photosystems within coral's zooxanthellae. 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, is developing the first product to use both satellite-derived light and temperature data to predict photosystem stress that leads to bleaching. The methodology uniquely expresses both thermal stress and excess-light stress as an equivalent light stress value, allowing light and temperature data to be combined. Named Light Stress Damage (LSD), this product will use NOAA's next-generation daily 5 km blended satellite SST data and NOAA's surface light product from geostationary satellites. This daily product will be released for the Greater Caribbean region first, then the Great Barrier Reef, and eventually globally.

## Discussion

While satellite SST-based products have been successful in monitoring coral reef environmental conditions, continuous improvements to existing products are needed, both to adapt to new satellite technology and to address new environmental threats. 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) suggests that Ocean Color, Synthetic Aperture Radar (SAR), and Ocean Surface Vector Winds (OSVW) are 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. It will provide guidance to enhance CRW's SST products in the new-generation DSS and will provide important information for coral reef management.

## Acknowledgement

We are grateful to funding from the National Oceanic and Atmospheric Administration's Coral Program, Climate Program Office's Sectoral Applications Research Program, the National Centers for Environmental Prediction, and NASA and to all who have contributed to the development of Coral Reef Watch. The manuscript contents are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the US Government.

## References

Coral Reef Watch (2012) CFS Seasonal Bleaching Outlook System. Available online at http://coralreefwatch.noaa.gov/satellite/bleachingoutlook_cfs/outlook_cfs.html

Eakin CM, Liu G, Chen M, Kumar A (2012) Ghost of bleaching future: Seasonal Outlooks from NOAA's Operational Climate Forecast System. Proc 12th Int Coral Reef Sym (this volume)

Eakin CM, Morgan JA, Heron SF, Smith TB, Liu G, et al. (2010) Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. PLoS ONE 5(11): e13969

Earth System Research Laboratory (2011) GLOBALVIEW-$CO_2$ dataset. Available online at: http://www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_intro.html

Gledhill DK, Wanninkhof R, Millero FJ, Eakin CM (2008) Ocean acidification of the Greater Caribbean Region, J Geophy Res - Oceans 113(C10)

Glynn PW, D'Croz LD (1990) Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. Coral Reefs 8:181-191

Goreau T, McClanahan T, Hayes R. Strong A (2000) Conservation of coral reefs after the 1998 global bleaching event. Conservation Biology 14:5-15

Heron SF, Willis BL, Skirving WJ, Eakin CM, Page CA, et al. (2010) Summer Hot Snaps and Winter Conditions: Modelling White Syndrome Outbreaks on Great Barrier Reef Corals. PLoS ONE 5(8): e12210. doi:10.1371/journal.pone.0012210

Liu G, Matrosova LE, Penland C, Gledhill DK, Eakin CM, et al. (2009) NOAA Coral Reef Watch Coral Bleaching Outlook System. Proc 11th Int Coral Reef Sym 951-955

Liu G, Strong AE, Skirving WJ, Arzayus LF (2006) Overview of NOAA Coral Reef Watch Program's Near-Real-Time Satellite Global Coral Bleaching Monitoring Activities. Proc 10th Int Coral Reef Sym 1783-1793

Liu G, Skirving W, Strong AE (2003) Remote sensing of sea surface temperatures during 2002 Barrier Reef coral bleaching. EOS 84(15):137-144

Montgomery RS, Strong AE (1994) Coral Bleaching Threatens Ocean, Life. EOS 75(13): 145-147

Penland C, Matrosova L (1998) Prediction of tropical Atlantic sea surface temperatures using linear inverse modeling. J Climate 11:483–496

Saha S, Nadiga S, Thiaw C, Wang J, Wang W, et al. (2006) The NCEP Climate Forecast System. J. Climate 19: 3483-3517

Skirving WJ, Heron M, Heron SF (2006a) The hydrodynamics of a bleaching event: implications for management and monitoring. Coastal Estuarine Stud 61:145-161

Skirving WJ, Strong AE, Liu G, Arzayus F, Liu C, Sapper J (2006b) Extreme events and perturbations of coastal ecosystems. In L.L. Richardson & E.F. LeDrew [Eds.], Remote Sensing of Aquatic Coastal Ecosystem Processes. Remote Sensing and Digital Image Processing, Vol. 9, Springer. pp 11-26

Strong AE, Lucas EY, Eakin CM, Rauenzahn J, Chang P, Ignatov A, Liu G, Maturi E, Miller L, Pichel W, et al. (2012) Enhanced Satellite-Remote Sensing for Coral Reef Management: Next Decade. Proc 12th Int Coral Reef Sym (this volume)

Strong AE, Liu G, Kimura T, Yamano H, Tsuchiya M, Kakuma S, van Woesik R (2002) Detecting and monitoring 2001 coral reef bleaching events in Ryukyu Islands, Japan using satellite bleaching hotSpot remote sensing technique. Proc 2002 IEEE Int Geosci Remote Sensing Symp and 24th Canadian Symp Remote Sensing, Toronto, Canada

Strong AE, Barrientos CS, Duda C, Sapper J (1997) Improved satellite techniques for monitoring coral reef bleaching. Proc 8th Int Coral Reef Symp 1495-1498

Wellington GM, Glynn PW, Strong AE, Navarrete SA, Wieters E, Hubbard D (2001) Crisis on coral reefs linked to climate change. EOS 82:1-5

Zhang HM, Bates JJ, Reynolds RW (2006) Assessment of composite global sampling: Sea surface wind speed. Geophysical Research Letter 33: L17714, doi:10.1029/2006GL027086