Decision Support Tool Evaluation Report for Coral Reef Early Warning System (CREWS) Version 7.0

Applied Sciences Directorate Coastal Management Team
John C. Stennis Space Center, Mississippi

National Aeronautics and
Space Administration

John C. Stennis Space Center
SSC, Mississippi 39529–6000

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Applied Sciences Directorate Coastal Management Team
Callie Hall, *NASA ASD*
Vicki Zanoni, *NASA ASD*
Eurico D'Sa, *SSAI – Lead Author*
Don Holland, *SSAI*
Greg Terrie, *SSAI*
Slawomir Blonski, *SSAI*
Mary Pagnutti, *SSAI*
Joseph P. Spruce, *SSAI*

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Executive Summary

Coastal Management is one of 12 elements in the NASA Science Mission Directorate's National Applications program. Through the Coastal Management element, NASA's Applied Sciences Directorate extends products derived from Earth science data, models, technology, and other capabilities into partners' decision support tools (DSTs) to address coastal (including marine and ocean) management issues. NASA partners with other Federal agencies, such as the National Oceanic and Atmospheric Administration (NOAA), and with national-regional organizations that have coastal management responsibilities and mandates to support coastal resource managers.

This report describes the Coral Reef Early Warning System (CREWS) DST and discusses the potential of NASA remote sensing data and modeling products for enhancing the DST. CREWS is operated by NOAA's Office of Oceanic and Atmospheric Research as part of its Coral Reef Watch program in response to the deteriorating global state of coral reef and related benthic ecosystems. NOAA is also playing an important role in supporting the U.S. Coral Reef Task Force which was created by Executive Order P.L. 13089, and calls for the conservation and protection of the nation's coral reefs. Specifically, NOAA has been monitoring and providing alerts on coral "bleaching" or whitening events that result in the degradation of coral reefs worldwide. Although many different hypotheses exist as to the cause for coral bleaching, strong evidence supports unusually warm sea surface temperatures (SSTs) as contributing to coral reef mortality associated with bleaching. The CREWS DST presently uses field measurements of SST and other ancillary data collected at coral reef stations to produce Web alerts on coral bleaching as well as to provide validation of NOAA satellite SST products used for coral bleaching predictions. Coral reefs have also been shown to be affected or damaged by water quality indicators, such as high concentrations of phytoplankton biomass and suspended sediments. CREWS will also be used to send alerts on declining water quality indicators to initiate mitigation efforts.

In addition to SSTs, the two most important parameters utilized by the CREWS network in generating coral reef bleaching alerts are 1) wind speed and direction and 2) photosynthetically available radiation (PAR). NASA remote sensing products are available to enhance CREWS in these areas, including SST and PAR products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and wind data from the Quick Scatterometer (QuikSCAT). CREWS researchers are also interested in three additional parameters that are associated with water quality around coral reefs and are potentially useful in coral reef health monitoring: chlorophyll, chromophoric dissolved organic matter (CDOM), and salinity. Chlorophyll and CDOM are directly available as NASA products, while rainfall (another available NASA product) can be used as a proxy for salinity. Other potential NASA inputs include surface reflectance products from MODIS, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Landsat. This report also identifies NASA-supported ocean circulation models, such as the Ocean General Circulation Model (OGCM), and products from future satellite missions that would be useful in enhancing the CREWS DST.

While NASA inputs have the potential for enhancing CREWS, this report addresses the dearth of previous application of Earth science products in coral reef regions and identifies products and models that need verification and validation efforts to support the CREWS DST. Other issues to consider include spatial and temporal resolution, data continuity, and data formatting. Based on the successful use of NASA inputs by the CREWS DST, these products could be further extended to support additional coral-reef-based DSTs (e.g., NOAA's coral bleaching reports based on SST anomalies).

1.0 Introduction

As part of a systematic approach to extending the benefits of NASA's Earth science research results to the broader community, NASA's Science Mission Directorate has identified 12 applications of national priority. These 12 national applications have been determined using criteria including the consideration of potential socio-economic return, application feasibility, appropriateness for NASA, and partnership opportunities (Figure 1). This report is an element of the Coastal Management national application. The Coastal Management application addresses issues of concern and decision-making related to coastal zones, near-shore environments, and marine and open-ocean activities and includes wetlands, estuaries, reefs, oceanic islands, and coasts of large inland waters. The Coastal Management application focuses on decision support tools (DSTs) related to coastal, marine, and oceanic regions that serve such classes of issues as environmental resource management, economic management, mitigation and adaptation of sea level changes, and public and environmental health.

The National Oceanic and Atmospheric Administration (NOAA) operates a number of DSTs related to coastal environments and is a key partner with NASA in the Coastal Management national application. Coastal management, one of NOAA's many responsibilities, includes oversight of coral reefs that have in recent times experienced environmental degradation. NOAA has initiated the Coral Reef Watch Program to provide long-term monitoring of coral reefs and to provide early warnings of detrimental coral reef conditions, such as bleaching. NOAA's Office of Oceanic and Atmospheric Research (OAR) operates the Coral Health and Monitoring Program (CHAMP), and the Coral Reef Early Warning System (CREWS) is part of this monitoring and decision support system (DSS) for coral reefs. This report evaluates potential enhancements of the CREWS DST with NASA Earth science inputs and the possibility of extending this support to other NOAA coral-reef-based DSTs.

Figure 1. NASA Science Mission Directorate applications of national priority.

1.1 CREWS Overview

Coral reefs worldwide are experiencing the phenomenon known as coral bleaching or whitening with increasing frequency. Coral bleaching is caused by loss of pigmented algae that live in the coral host and on which the coral depend for survival. In response to this disturbing increase in coral bleaching, NOAA's Coral Reef Watch (CRW) program is installing *in situ* monitoring stations at strategic coral reef areas to establish long-term datasets and to provide near-real-time information products and field data for validation of NOAA's satellite-based sea surface temperature (SST) products used for coral bleaching predictions. The suite of stations, which transmit data hourly, together with custom artificial intelligence software that analyzes the data, is called the Coral Reef Early Warning System (CREWS) network (Hendee et al., 2002).

NOAA's funding directly related to assessment and monitoring coral reef health has increased from $2.4 to $8.6 million from 1999 to 2001 and is increasing to expand programs such as CREWS. A casual Internet search of NOAA Web sites, or of coral research in general will reveal the emphasis that NOAA places on coral reef health. A wealth of information is available on efforts by NOAA and by numerous other organizations to map, monitor, and provide information on conditions of coral reefs worldwide. A much abbreviated version showing CREWS' place in NOAA's organizational structure is shown in Figure 2. NOAA's four line organizations–the National Oceanographic Service, the Office of Oceanic and Atmospheric Research (OAR), NESDIS, and the National Marine Fisheries Service (NMFS)–collaborate within the CRW, using it as an umbrella enterprise with programs and projects in each of the four organizations. NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) (part of OAR) operates the Coral Health and Monitoring Program (CHAMP) that includes CREWS and is discussed in detail in the remainder of this report.

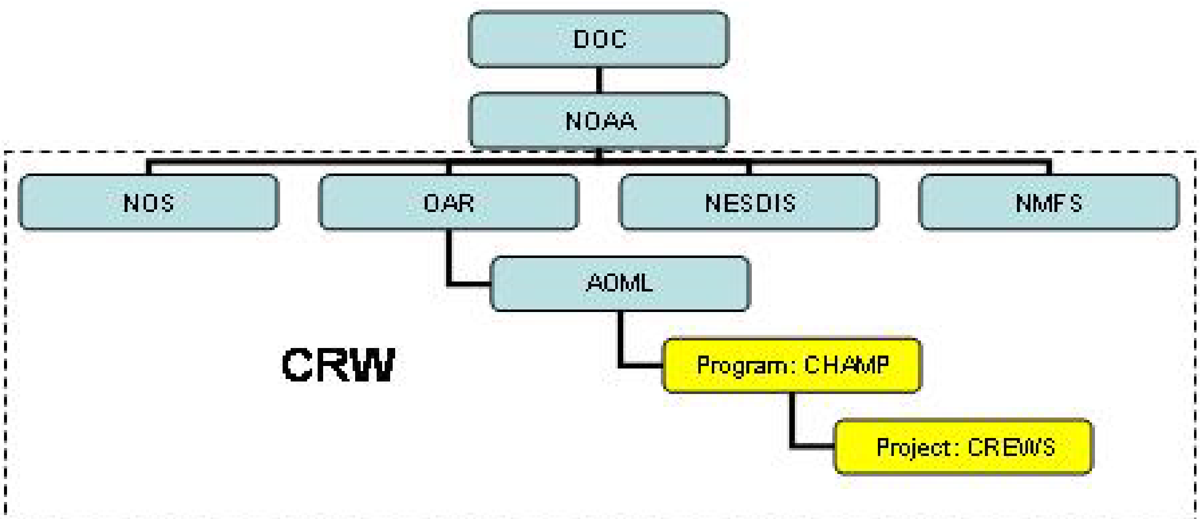
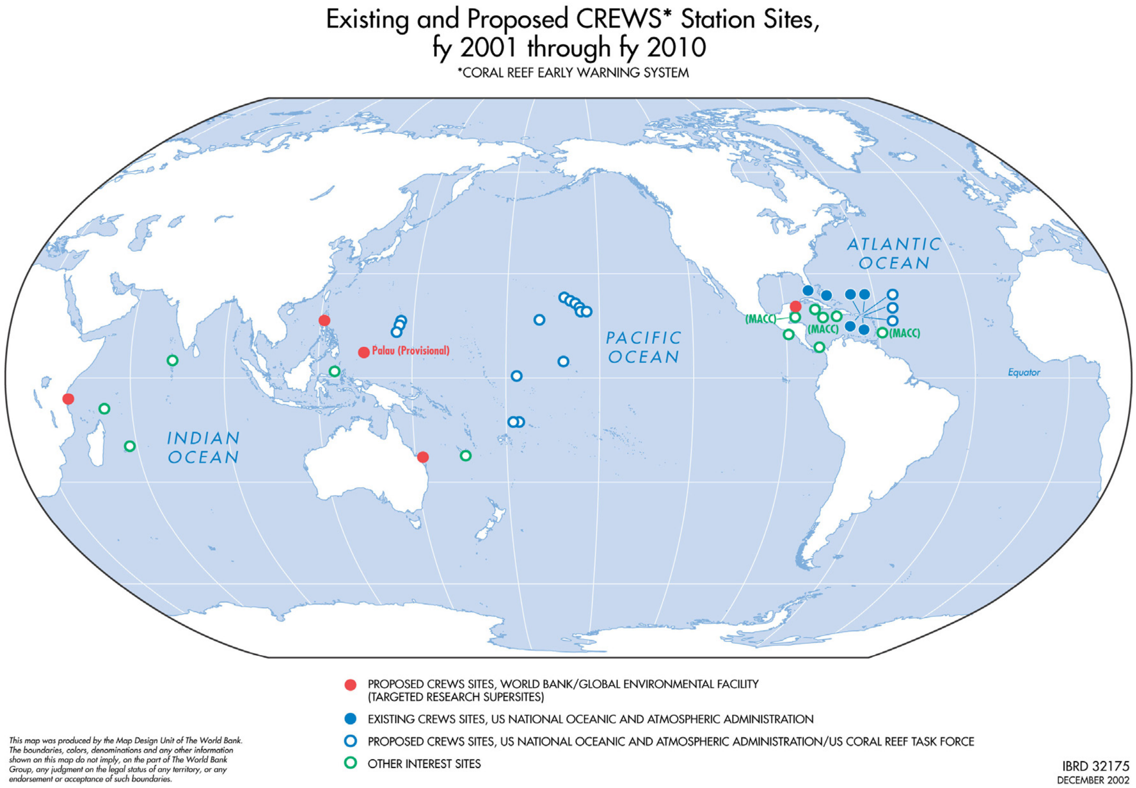


Figure 2. NOAA's organizational structure and the various line organizations within NOAA that are involved in coral reef work.

The CREWS system was initially implemented in 1997 and was based on the ocean monitoring stations (funded by NOAA and operated by the Florida Institute of Oceanography) located at various coral reefs in the Florida Keys. The first CREWS station operated under NOAA's CRW program was installed as a buoy at Lee Stocking Island on 25 May 2001. NOAA has committed to the installation of meteorological and oceanographic monitoring stations at all major United States coral reef areas by 2010 and is interested in extending these stations to many other sites worldwide (Figure 3).



Source: National Oceanic and Atmospheric Administration, 2004
(http://www.coral.noaa.gov/crw/stations.shtml)

Figure 3. Proposed locations for CREWS field stations at various coral reef sites worldwide.

Note: While six sites have been shown as existing CREWS sites in the figure above, only two sites are currently operational: one in the Bahamas and the other in the U.S. Virgin Islands. A third site located in the Florida Keys (consisting of seven monitoring stations) also feeds its field data to the CREWS network. These stations, however, are operated by the Florida Institute of Oceanography.

Presently two CREWS stations are in operation: one in the Bahamas and the other in the U.S. Virgin Islands. NOAA has an aggressive plan to set up at least two field stations every year that could total 18 to 20 coral reef stations (e.g., 2 in American Samoa, 6 in Hawaii, 2 in Puerto Rico, 2 in Virgin Islands) within the next few years. The World Bank is also supporting the establishment of a field station in the Great Barrier Reef in Australia.

The basic suite of meteorological and air-based sensors at the present CREWS stations performs the following measurements: 1) air temperature, 2) wind speed and direction, 3) barometric pressure, 4) photosynthetically available radiation (PAR), and 5) ultraviolet radiation (UVR). The basic suite of oceanographic sensors measures 1) sea temperature, 2) salinity, 3) PAR, and 4) UVR (at 1 meter nominal depth). Based on the field data at these two stations, CREWS produces automated electronic mail and World Wide Web alerts when conditions are thought to be conducive to or predictive of coral bleaching. The CREWS network is in the initial stages of development and currently can be considered primarily as a research tool; many of the alerts presently generated are providing feedback to researchers to evaluate and fine-tune the rule-based expert system. However, NOAA plans to convert CREWS into an operational system.

At each of the field stations, local maintenance and calibration of the sea temperature sensor ensures high-quality data. Local collaborators also provide feedback on the presence and progress of coral bleaching and thus validate coral bleaching predictions made by CREWS. In addition both the local collaborators and CREWS has helped the "HotSpots" coral bleaching predictions made by NOAA National Environmental Satellite, Data, and Information Service (NESDIS) that maps warm-season sea surface thermal anomalies worldwide. HotSpots are anomalies above a satellite-derived climatological Maximum Monthly Mean (MMM) SST. An increase of 1°C above the MMM SST during summer is a general threshold for inducing coral bleaching (Jokiel and Coles, 1990).

Another CRW program, operated by the Florida Institute of Oceanography, is located at the Keys Marine Laboratory on Long Key in the Florida Keys. This program also provides hourly data from up to seven meteorological and oceanographic monitoring stations situated throughout the Florida Keys Marine Sanctuary and Florida Bay (e.g., Molasses Reef, Sombrero Key, NW Florida Bay). As part of the CRW program, data from the Florida Keys stations are also integrated into the CREWS to alert Florida Keys National Marine Sanctuary management and coral researchers, via e-mail, when conditions are conducive to coral bleaching.

Early warnings of coral bleaching events will provide researchers and sanctuary managers an ability to monitor the various phases of bleaching events potentially enabling mitigation efforts to be initiated. Although mitigation efforts associated with SST increases are not feasible, monitoring of water quality indicators such as phytoplankton biomass and suspended sediments provides an opportunity to coastal managers to initiate efforts to reduce point sources of pollution that may degrade water quality. Another intended outcome of CREWS, through its *in situ* network and associated research, is to identify models that can best predict coral bleaching. The *in situ* data and the associated research conducted will improve confidence in a model's predictive ability. Improved model confidence can then be reported to NOAA leadership, to the U.S. Congress, and to national and international environmental policy-makers to affect mitigation plans and procedures (e.g., calls for reductions in greenhouse gases to reduce global warming). Another important application of the CREWS DST is for the Marine Protected/Park Area (MPA) managers to use the CREWS alerts to determine levels of reef stress so that they could make decisions on reefs being off-limits for certain activities to reduce reef stress.

1.2 Related Activities

NASA partners with Federal agencies and regional/national organizations that have coastal management responsibilities and mandates to support coastal resource managers. Under Executive Order 13089, which calls for the conservation and protection of the nation's coral reefs, NOAA, the United States Geological Survey (USGS), and NASA were designated as the federal co-chairs of the Mapping and Information Synthesis Working Group to lead the development of a comprehensive coral reef mapping plan. The Executive Order also states that to the extent feasible, remote sensing capabilities should be developed and applied to this effort and local communities should be encouraged to participate. The Working Group identified two high-priority issues: 1) digital coral reef ecosystem mapping, and 2) the development of remote sensing technologies for routine, operational monitoring of coral reefs and change detection. In pursuance of these goals, some NASA-sponsored partnerships that have been initiated include the following: 1) NASA Goddard Space Flight Center (GSFC) and NOAA/NESDIS are working together to develop baseline global shallow bathymetry reef maps using ocean color satellite data, and 2) NASA has funded a global coral reef mapping project at the Institute for Marine Remote Sensing, University of South Florida. NASA has also supported collaboration with international non-governmental organizations such as the World Resources Institute (WRI) and ReefBase. WRI supports projects that evaluate threats to coral reefs from coastal development, marine pollution, pollution and sedimentation from inland sources, and overexploitation of resources. Through NASA support, Florida International University has been collaborating with WRI in comparing different sources of land cover maps with Landsat 7 data for the Florida Keys. ReefBase is the premier online information system on coral reefs and serves as the primary data archive and distribution center for the International Coral Reef Action Network. As part of its collaboration with NASA, ReefBase has an online interactive map server that allows viewing and interactive assembly of NASA remote sensing imagery of reefs and shallow bathymetry products.

In response to the U.S. Coral Reef Task Force goal of establishing long-term datasets, NOAA is setting up a network of CREWS field stations in all major U.S. coral reef areas. NASA partnership with NOAA on CREWS would facilitate the integration of NASA Earth science data to this coral reef DST. On a long-term basis, the data and alerts from the CREWS network are intended to help decision makers (e.g., NOAA, NASA, the U.S. Environmental Protection Agency, the USGS, and Congress) to evaluate and link global climate change issues to the state of coral reefs worldwide and to influence mitigation plans and policies.

1.3 Systems Engineering Approach

This evaluation is based on the systems engineering approach outlined in Figure 4, which is designed to integrate NASA measurements and predictions effectively within a DST. The evaluation, verification and validation (V&V), and benchmarking of NASA observations and model predictions within CREWS are critical components of the overall evaluation and review of the DST. Definitions of the terms evaluation, verification, validation, and benchmarking are provided in Appendix A.

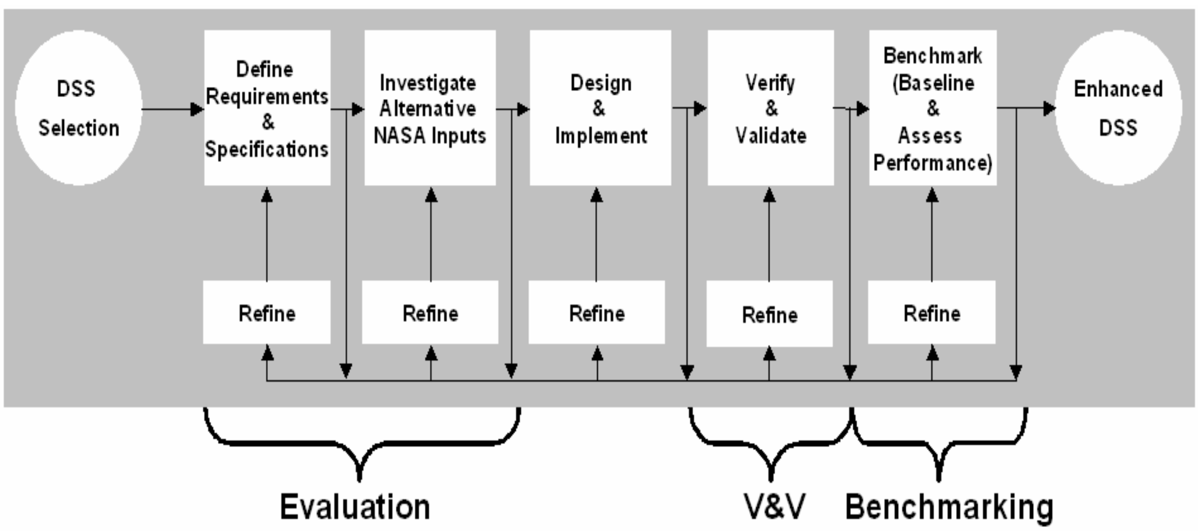


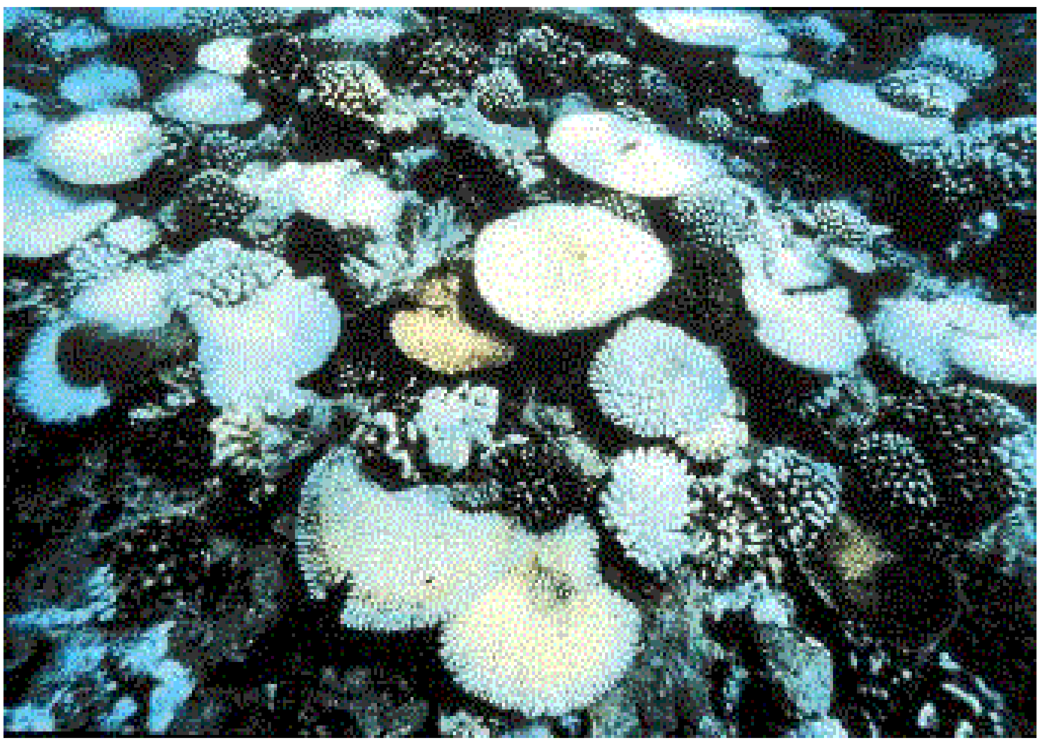
Figure 4. Systems engineering approach (adapted from Bahill and Gissing, 1998).

In general, the evaluation phase involves understanding the requirements for and technical feasibility of Earth science and remote sensing tools and methods for addressing CREWS requirements. The V&V phase includes measuring the performance characteristics of data, information, technologies, and/or methods and assessing the ability of these tools to meet the requirements of the DST. In the benchmarking phase, the adoption of NASA inputs within CREWS and the resulting outcomes and impacts will be documented. Use of systems engineering principles leads to scalable, systemic, and sustainable solutions and processes, which in turn contribute to the success of the mission, goals, and objectives of CREWS and coral reef managers. This report documents the evaluation of the CREWS DST and was developed based on information provided by NOAA, by refereed journal articles, by various other references, by NASA's Science Mission Directorate strategic plans, and by input from other NASA centers.

2.0 Description of CREWS DST

2.1 Background on Coral Bleaching

Most reef-building corals contain photosynthetic algae, called zooxanthellae, that live in their tissue. The corals and algae have a symbiotic relationship. The coral provides the algae with a protected environment and compounds their need for photosynthesis. In return, the algae produce oxygen, help the corals to remove waste, and provide nutrients that help reef-building corals create reef structures. When a coral bleaches, it loses its zooxanthellae and will die within a matter of weeks unless the zooxanthellae can be replaced. The term "bleaching" is used because the unique and beautiful colors of living corals are due to the colors of the zooxanthellae in coral tissue, and when the zooxanthellae are lost, corals appear white, or bleached (Figure 5).



Source: National Oceanic and Atmospheric Administration, 2004

Figure 5. A coral reef undergoing bleaching or whitening.

While many different hypotheses exist as to the cause behind coral bleaching, the strongest evidence points to unusually warm sea temperatures around the corals as the main contributory factor (Glynn, 1993). Coral bleaching events worldwide have been linked to SSTs rising and staying as little as 1°C higher than the usual average monthly maximum SST during the hottest months of the year (Goreau and Hayes, 1994). In Jamaica, significant coral bleaching and mortality occurred when SST remained at 29.3°C or higher for one month (Hoegh-Guldberg, 1999). Therefore, in the Caribbean and Florida Keys, coral bleaching is likely to occur when SSTs rise and stay above this thermal threshold. Mass coral bleaching was first recognized on the Pacific coast of Panama following the 1982-83 El Niño event (Glynn, 1984), which resulted in elevated water temperatures. The 1997-98 El Niño event was the strongest on record to date and has resulted in large-scale coral bleaching and death across the globe (Wilkinson et al., 1999). In the Indian Ocean, severe to catastrophic bleaching occurred in the Maldives Islands, in the Lakshadeep Islands, and in the Andaman Islands (about 80%), followed by large-scale mortality of the shallow coral reefs (Wilkinson et al., 1999). In the Florida Keys, bleaching of inshore corals began in mid-June 1998. Severe bleaching was reported in inshore reefs (50–90%), coincident with 32°C *in situ* SSTs (Toscano et al., 2001). During this time, offshore reef areas of the Florida Keys also reported high incidences of bleaching.

NOAA/NESDIS has been using the near-real-time global 50-km twice-weekly nighttime Advanced Very High Resolution Radiometer (AVHRR) SST products, such as HotSpots maps (Figure 6) and Degree Heating Weeks (DHW) charts, as indices of coral bleaching related to thermal stress (Strong et al., 1997; Strong et al., 1998; Toscano et al., 1999; Liu et al., 2001). The HotSpot mapping effort has predicted bleaching over large areas of the tropics and has provided real-time global spatial data on the extent and level of thermal stress to researchers and to resource management specialists (Toscano et al., 2001). NOAA is generating DHW charts using AVHRR SST satellite data on an experimental basis. One DHW is equivalent to one week of SST one degree Celsius warmer than the expected summertime maximum (mean monthly maximum). These charts indicate the length of time that coral reefs experience thermal stress and are produced biweekly at 50-km resolution. Data and alerts from CREWS also provide surface-truth to NOAA satellite SST products used for coral bleaching predictions or for HotSpot products.

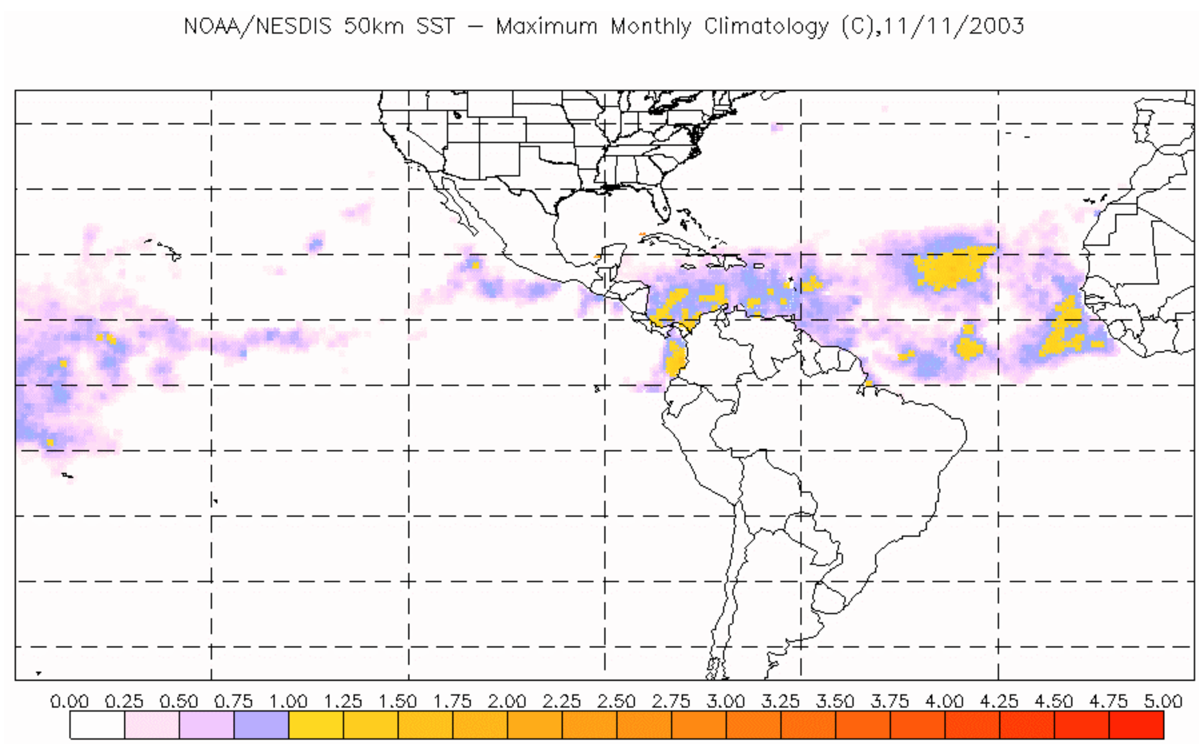


Figure 6. An example HotSpot image map being produced by NOAA using AVHRR SST data.

However, it is recognized that a single parameter, such as thermal stress, may not be the only factor to force bleaching events (Hughes and Connell, 1999). Stress caused by pollution, photosynthetically available radiation, changing salinity, and bacteria can also result in coral bleaching. Different coral reef systems show significant differences in bleaching response that also depend on depth and coral taxa. For example, in the Great Barrier reef during the large scale bleaching of 1998, one type of hydrocorals

(Millepora spp.) was found to be the most susceptible taxa with 85% mortality, while the other taxa (Cyphastrea, Turbinariea, and Galaxea) were relatively unaffected by bleaching (Marshall and Baird, 2000). Biological effects of bleaching include reduced growth, reduced reproduction, and increased mortality of corals. Ecological implications include significant reductions in cover of susceptible species, changes in community composition, decrease in species diversity, and associated decreases in reef growth and habitat diversity.

While environmental conditions conducive to coral bleaching have been reliably documented, uncertainty still exists regarding the local severity of bleaching and the community-level changes that will result from a predicted bleaching disturbance. This uncertainty is mainly due to interspecific and intraspecific variability in the effects of bleaching on corals (Marshall and Baird, 2000). In addition to temperature, other stressors on coral reefs include salinity changes, turbid water, and exposure during extreme low tides. Based on these factors, satellite-derived SST data may need to be complemented by field data comprising additional variables, such as wind speed and light field intensity. CREWS considers various physical factors and issues “bleaching alerts” when coral bleaching appears likely. The CREWS software evaluates the intensity of PAR, wind speed, and SSTs when issuing coral bleaching alerts. The effectiveness of this system was demonstrated during the 1997-98 El Niño event when bleaching was predicted and occurred on Sombrero Reef in the Florida Keys. These alerts help researchers to be present at a study site if conditions appear to be optimal for coral bleaching and thus provide a better understanding of the phenomenon (Hendee et al., 2001). Other factors contributing to coral reef decline have been attributed to water quality indicators, such as high concentrations of chlorophyll, chromophoric dissolved organic matter (CDOM), and salinity. However, the extent of their influence on coral bleaching and coral stress is still a subject of active study. Field measurements of some of these parameters are under consideration at the CREWS stations. Future integration of these measurements into the CREWS DST will allow mitigation efforts (e.g., setting up of a wastewater treatment plant, or official designation of no-discharge zones for boater sewage) to be initiated because of anthropogenic influences on coral reefs.

2.2 Technical Description of CREWS

The CREWS network has been operating since 2001 with the activation of the first station at North Norman’s Reef, Bahamas, followed by a second station at the Salt River Bay National Historical Park and Ecological Preserve in St. Croix, U.S. Virgin Islands. Figure 7 gives an aerial view of the coral reefs at these two locations. NOAA plans to expand the network of CREWS stations in the Bahamas and in American Samoa to include 18 stations by 2006 and other major stations by 2010.

Source: National Oceanic and Atmospheric Administration, 2004
(http://www.coral.noaa.gov/crw/bahamas.html & http://www.coral.noaa.gov/crw.html)

Figure 7. Aerial view of coral reefs in the Bahamas (top panel) and a higher resolution view of coral reefs in the U.S. Virgin Islands (bottom panel) where the two CREWS field stations are in operation.

The new monitoring station at the U.S. Virgin Islands and the Bahamas features a radically new design (Figure 8) that will be the basis of future CREWS stations installed throughout the Caribbean and the Pacific. Oceanographic instruments (e.g., temperature, conductivity, fluorescence, and ultraviolet-B sensors) are located at a nominal depth of 1 meter below the surface and 1 m above the bottom, rising and falling with waves and tide. Atmospheric instruments (e.g., wind speed/direction, barometric pressure, temperature, and PAR sensors) are located on a platform at a height of 5 meters to measure the critical air mass right above the ocean while mast-mounted anemometers at a height of 10 meters accurately measure wind speed and direction. Field technicians maintain the sensors and periodically conduct calibration checks of the *in situ* temperature sensors. Infrastructure is in place to install additional instruments on the CREWS platforms to measure partial carbon dioxide and Pulse Amplitude Modulated fluorometry.

Another parameter of interest to CREWS is chromophoric dissolved organic matter (CDOM). This parameter is planned to be acquired through field sampling. These new sensors and measurements will provide data to researchers on additional parameters that could be useful to assess the health of coral reefs.

Source: http://www.accessnoaa.noaa.gov/crews.html

Figure 8. The new instrumented monitoring stations that have been deployed at North Norman's Reef, Bahamas and the U.S. Virgin Islands and form the basis of future CREWS stations to be installed throughout the Caribbean and the Pacific.

The data collected from the *in situ* sensors at the two stations are averaged over one hour and then sent from the station to a Geostationary Operational Environmental Satellite (GOES), where they are then retransmitted to a land-based NOAA station at Wallops Island, Virginia. Custom Unix automated programs at AOML collect the previous 72 hours worth of data from Wallops Island once in the morning, then every hour from approximately 6:30 a.m. through 6:30 p.m. (Hendee et al., 2002). Once acquired, the raw data are posted to the CRW Web site (NOAA, 2004) and then processed by the CREWS software.

The software has two components: the first stage prepackages the data to make them suitable for use by the second stage, which is the application-specific knowledge base for the problem domain in question (e.g., coral bleaching). The CREWS expert system software screens the data in near-real-time to test for data flags that are used to issue "alerts" when conditions are thought to be conducive to coral bleaching. A simplified diagram and flowchart showing the various components of CREWS are shown in Figure 9. The CREWS software evaluates the intensity of solar radiation, wind speed, and SST when issuing coral bleaching alerts. For example, PAR measurements, in combination with wind speed and temperature, allow estimates of solar energy that penetrates water. Exposure of corals to very high sunlight under low wind speed could photo-damage the zooxanthellae, making a bleaching response more likely. Alternately, an alert could be issued when the SST at the sampling site exceeds a threshold temperature of 29.3°C for over two weeks. These alerts are sent by e-mail to coral reef managers and research scientists and are also available on the Web site (NOAA, 2004) for the benefit of the general public. These alerts help reef managers and researchers obtain a better understanding of the coral bleaching phenomenon by providing data and conditions thought to be conducive for bleaching events. *In situ* data from the CREWS stations are also used to validate and verify AVHRR-derived SSTs used in generating the NOAA/NESDIS coral bleaching predictions or HotSpots. At each CREWS station, local collaborators also provide feedback on the presence and progress of coral bleaching and thus validate coral bleaching predictions made by NESDIS (e.g., satellite HotSpots) and CREWS information products.

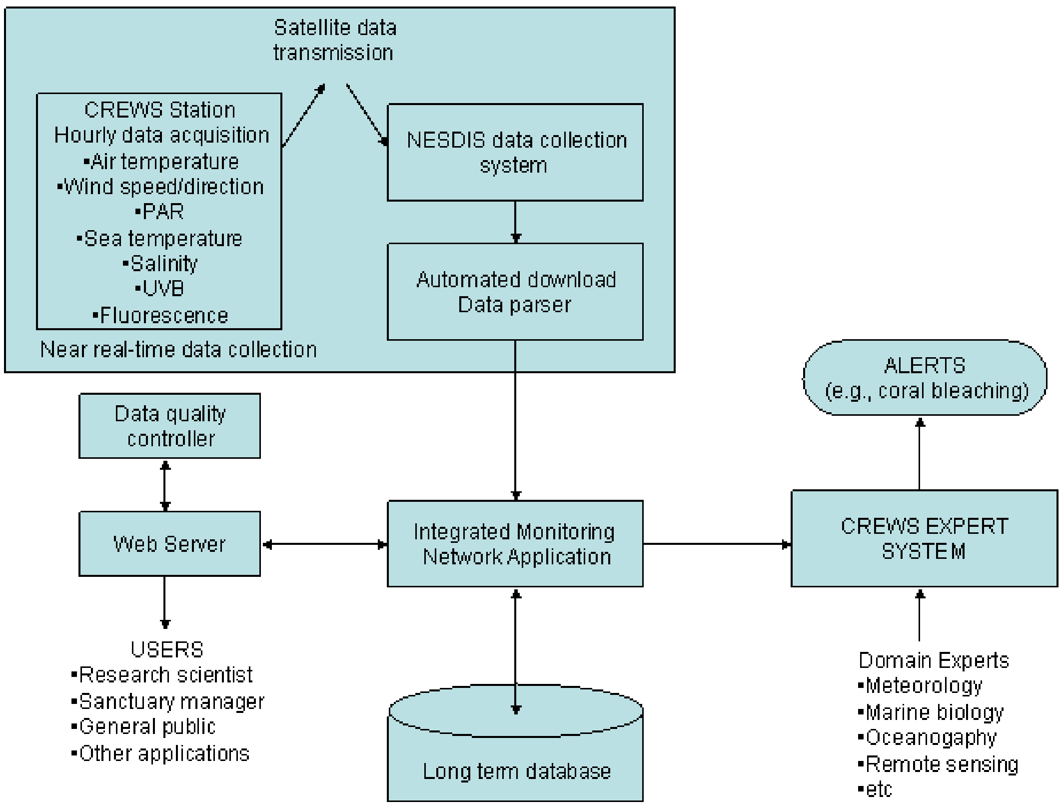


Figure 9. Simplified diagram and flowchart showing the various components of the CREWS system.

The three most important parameters utilized by the CREWS network in generating coral reef bleaching alerts are 1) sea temperature, 2) wind speed and direction, 3) light (photosynthetically available radiation or PAR and UV at 303, 305, 330, and 380 nm), and state of tide (i.e., high or low tides). The application of NASA Earth science products has the potential to enhance the CREWS DST through the integration of both remote sensing products and models. The three important parameters used for generating the bleaching alerts by CREWS are available from the NASA product stream. CREWS researchers are interested in two additional parameters that are associated with water quality around coral reefs and are potentially useful in coral reef health monitoring: chromophoric dissolved organic matter and salinity. Coral reefs have been shown to be sensitive to salinity variations (and hence to rainfall), while CDOM has been indicated to protect coral reefs by reducing the damaging effects of ultraviolet radiation. Both CDOM absorption and rainfall are two other potential NASA Earth science products that could also support the CREWS DST.

2.3 The CREWS Expert System

The CREWS expert system was developed for the near-real-time review of environmental conditions thought to be conducive to coral bleaching (Hendee, 1998; Hendee et al., 2001). Snapshots of the CREWS expert system and of a bleaching alert are shown in Figure 10. The CREWS expert system is based on the C Language Integrated Production System (CLIPS), a rule-based language developed at NASA's Johnson Space Center. Expert systems attempt to replicate the reasoning processes of experts in performing tasks based on relevant input data. The information is processed according to rules prescribed by experts. The knowledge base upon which the input is matched is generally represented by a series of IF/THEN statements called production rules. These production rules are written in consultation with experts, and they try to approximate as well as possible the expert's reasoning. If conditions are met for more than one production rule at the same time, the order of triggering for the rules is arranged according to the "salience" of the rule so that the rule with the highest salience is triggered first, then the rule with the next lowest salience, and so on. The degree of belief in the conclusion from the production rule is made in the case of CREWS as a subjective term; e.g., "not conducive," "possibly," "probably," or "almost certainly" for the occurrence of bleaching.

Research indicates that although bleaching occurs under different environmental conditions for different species, high sea temperature, alone or in combination with low wind speeds and/or high solar radiation, appears to the main stressor involved for most species. Variables such as temperature have been arbitrarily assigned to fall within one of eleven categories (based on time of day and season): unbelievably low, drastically low, very low, low, somewhat low, average, somewhat high, high, very high, drastically high, and unbelievably high. The following pseudocode represents one of the production rules of the CREWS coral bleaching module (Hendee et al., 2001):

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IF sea temperature is drastically high all day
AND wind speed is very low all day,
AND the tide is drastically low during midday,
THEN output alert:
        "Conditions are probably favorable for coral bleaching."
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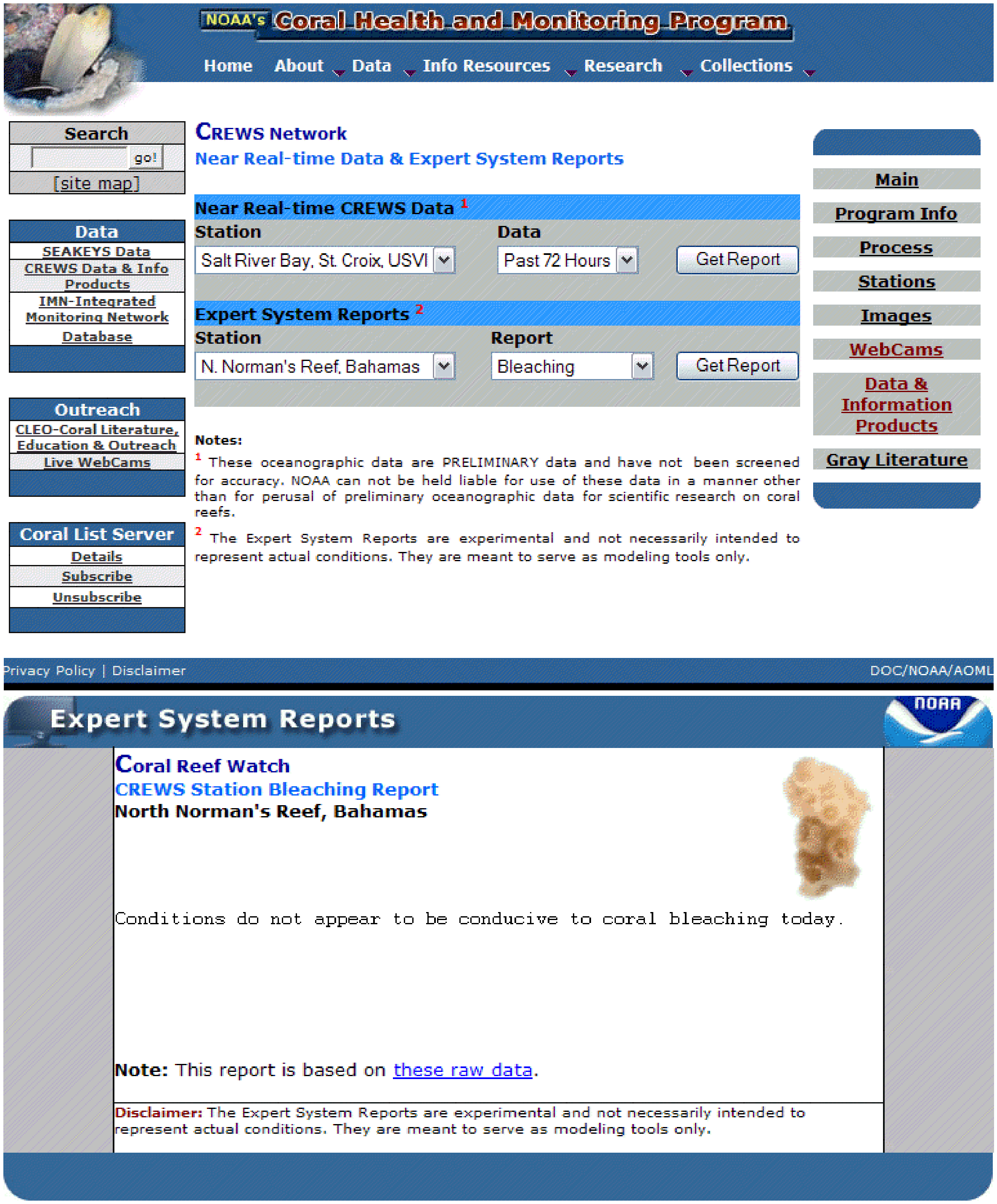


Source: National Oceanic and Atmospheric Administration, 2004
(http://www.coral.noaa.gov/crw/real_data.shtml & http://www.coral.noaa.gov/crews/es/cmrc2/bleach.shtml)

Figure 10. An example of the Web site for near-real-time CREWS data (top panel) and a corresponding bleaching report generated for the Bahamas (bottom panel).

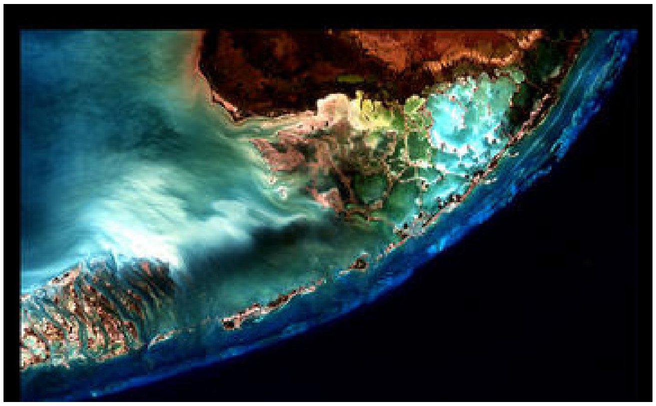
This particular production rule has a higher salience than other rules because it represents more extreme environmental stress. This rule would be the first to trigger when the prescribed conditions were met. Higher salience causes the expert system to assign a greater number of points to the rule. Fore example, if higher salience rules were to trigger a number of times within a week, a greater number of points would be accumulated for those particular conditions; therefore, if bleaching were to occur at that time, a greater weight to the validity of this particular model would accrue. On the other hand, if bleaching did not occur during that time, less validity would accrue, and the model (i.e., the production rules) would be adjusted as advised by the expert(s). Because several models can be coded at one time and the resulting points can be tabulated for these models at the end of each week, the expert can gain a fuller understanding of which environmental conditions were more conducive to coral bleaching (Hendee et al., 2001). Thus, in addition to temperature, which has been shown to be the most important bleaching indicator, CREWS provides *in situ* field data of other stressors (e.g., wind speed, solar radiation) that are potentially capable of causing coral bleaching. The alerts generated from this field data allow early detection of bleaching, including their intensity, as well as an understanding of the various environmental conditions that might or might not cause such events.

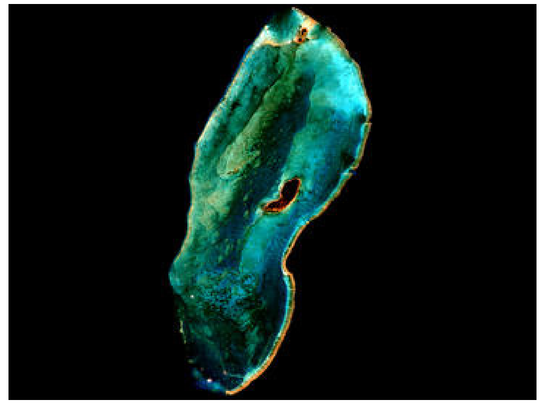
The CREWS system at present is not able to incorporate full image data into its data stream because of limitations of the CLIPS rule-based expert system on which CREWS is based. CREWS researchers plan to upgrade the expert system shell to a more powerful commercial system, the G2 (http://www.gensym.com). NOAA plans to develop and submit a proposal during 2004 to fund the purchase and installation of this expert system. G2 is a comprehensive object-oriented environment that is able to transform complex real-time data into useful information through knowledge-based reasoning and analysis. G2 also has the functionality to incorporate image data such as that obtained from NASA satellites. In both cases, the need to address data formatting issues related to integration of NASA products with the CREWS DST needs to be addressed.

3.0 Consideration of NASA Inputs

3.1 Remote Sensing of Coral Reefs and Past and Present NASA Contributions

Remote sensing has been useful in mapping and classifying coral reef types and in providing information on coral bleaching events worldwide. High-resolution remote sensing data, such as those from Landsat satellites, have been and are being used to characterize, map, and study coral reef systems (Figure 11) (Andréfouët and Payri, 2000; Gasch et al., 2000; Andréfouët et al., 2002). The NOAA AVHRR SST data is being used to generate coral reef HotSpot maps on a global scale. Coral reef bleaching of unprecedented extent and frequency occurred in the 1980s, in the 1990s, and peaked during the 1997-98 El Niño. Scientists have correlated these bleaching events to water temperatures elevated above "summertime" climatological means as the primary cause of massive bleaching during this period (Strong et al., 1997).





Source: Institute for Marine Remote Sensing, 2003
College of Marine Science, University of South Florida
(http://imars.usf.edu/corals/figure2.html)

Figure 11. Landsat 7 images of coral reefs located in Florida and in the Pacific. These high-resolution images provide fine detail of various coral reef features.

The USGS is collaborating with NASA to map the coral reef ecosystem in the northern Florida Keys using a new topographic NASA Experimental Advanced Airborne Research Lidar. This airborne instrument is designed to measure the bathymetric complexity of shallow reef substrates and uses a green wavelength Lidar. However, because of the complexity of coral reef morphology and varying bathymetry conditions, special challenges exist with respect to interpreting remote sensing data emanating from these regions. Coral reefs exist at varying water depths and are affected to varying degrees by temperature and solar radiation. Knowledge about the coral reef bathymetry might therefore aid in the interpretation of coral bleaching.

The USGS also performed mapping activities in the Pacific region that resulted in the agency's ability to use satellite sensors to detect large amounts of suspended sediments on the reefs due to land run-off events. The remote sensing data are being used to map and study spatial distribution, transport patterns, and amount of sediment introduced onto the reefs and their potential impact to the reefs. Water clarity is critical to coral reef health because it affects sunlight penetration and photosynthesis. The presence of large amounts of suspended sediments has been shown to affect coral reef growth (Miller and Cruise, 1995) and is an area of active research.

The application of remote sensing to coral reef studies has included data from airborne and satellite sensors, such as the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), Landsat, and other sensors of various spatial resolutions (Atkinson and Curran, 1997). Through the millennium Coral Reef Mapping Project at the University of South Florida's Institute for Marine Remote Sensing, NASA is funding the building of a database of Landsat and IKONOS images of coral reefs worldwide. The NASA Scientific Data Purchase (NASA, 2004) provided the Landsat 5 and IKONOS images (Figure 12). This dataset has allowed for the study of morphology and change detection in coral reefs (Andréfouët et al., 2001; Andréfouët et al., 2003).

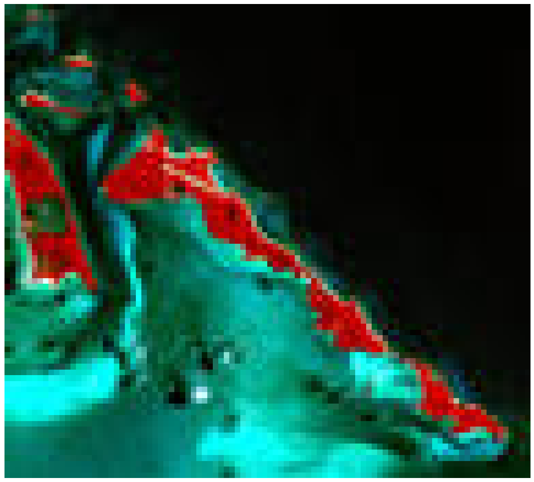


Figure 12. IKONOS image of Lee Stocking Island and North Norman Reef in the Bahamas. One of the two CREWS stations is based on this Island chain.

NASA researchers at Goddard Space Flight Center and at Johnson Space Center are presently collaborating with NOAA on the use of satellite imagery, such as from Landsat and SeaWiFS, to obtain estimates of algal biomass, bathymetry, and coral reef mapping (Robinson et al., 2000). A Web interface is being developed as a proof of concept for the use of remotely sensed Earth observations from various platforms in the mapping of coral reefs around the globe. This collaboration involves a large number of organizations including various NASA centers, NOAA, and individuals from around the world. The first global map of tropical shallow water has been created through a joint effort of NASA and NOAA wherein nearly 44,000 SeaWiFS scenes collected over 5 years were processed at 1-km resolution for waters shallower than 20–30 meters (Figure 13).

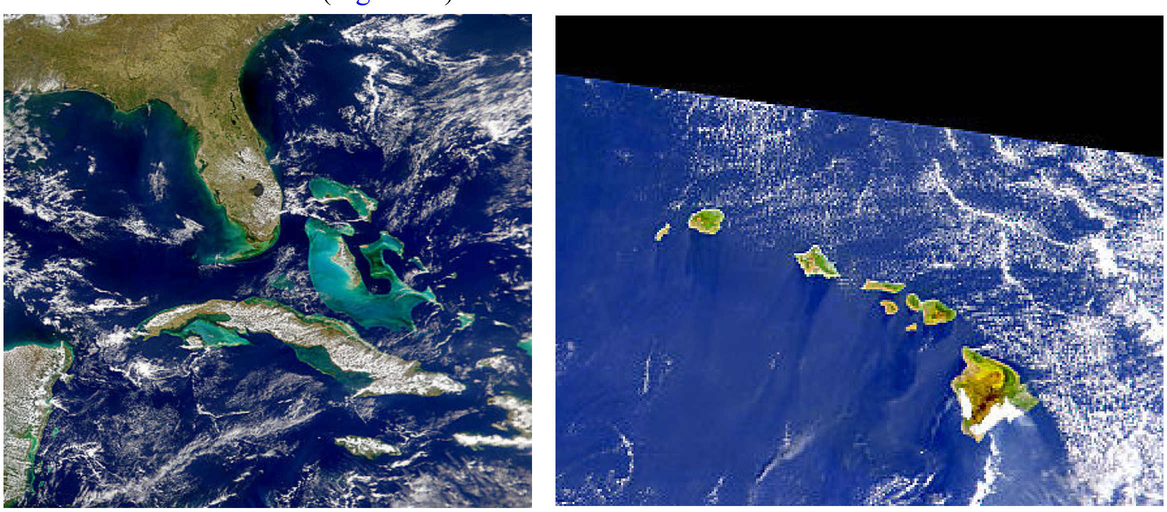


Figure 13. SeaWiFS images (1-km resolution) of coral reefs located in the Atlantic Ocean (left panel) and in the Hawaiian Islands in the Pacific Ocean (right panel). These data are being used on an experimental basis to determine bathymetry around coral reefs (Stumpf et al., 2003).

NOAA and NASA researchers are evaluating the use of SeaWiFS data, which has been mainly used for chlorophyll measurements, for extracting depth and bottom characteristics (Stumpf et al., 2003). This study complements the recent development of ReefBase (by the International Center for Living Aquatic Resources Management and the World Conservation Monitoring Center), which provides a comprehensive digital database of reefs for the entire globe. These efforts, however, do not include any support for the CREWS program.

3.2 CREWS DST Requirements and NASA Inputs

The previous sections have identified and discussed field data parameters (e.g., SST, winds, and PAR) that CREWS uses in generating bleaching alerts. Extending these alerts to monitoring coral reef health related to water quality issues (e.g., high concentrations of chlorophyll, salinity and CDOM) is also under active consideration. Literature surveys (Fuckar et al., 2004) have also indicated the potential of using ocean circulation models (developed through NASA support) to provide a better understanding and prediction capability to the CREWS DST. Presently, many of these DST requirements are not well defined because of the complexity of coral reef ecosystems, which can be both region- and species-specific. However some reasoned assumptions can be made regarding the CREWS requirements (e.g., spatial, temporal, and accuracy) based on literature survey and on discussions with the CREWS management. Table 1 and Table 2 list the various CREWS DST requirements (as derived from literature and from discussion with CREWS personnel) and the corresponding match of NASA inputs that could improve or enhance the DST capability. Detailed descriptions of each sensor and product discussed are provided in Appendix C. Because the CREWS effort is in its initial stages with only two field stations presently operational, an effort by NASA to provide added value to the DST is timely.

Moderate Resolution Imaging Spectroradiometer (MODIS) products (e.g., SST and Instantaneous PAR (IPAR)) and wind products from SeaWinds onboard the Quick Scatterometer (QuikSCAT) are of immediate utility to the CREWS DST. Other NASA products and models of value to the CREWS DST include MODIS ocean color products (e.g., chlorophyll concentrations, CDOM absorption), the Sea Surface Height (SSH) from the Jason altimeter, the 250 m and 500 m MODIS and moderate-resolution ASTER data, andproducts from the Tropical Rainfall Measuring Mission's (TRMM) Precipitation Radar (PR), TRMM Microwave Imager (TMI), and Visible Infrared Scanner (VIRS). MODIS is important as a transition to the next-generation moderate resolution sensor, the Visible/Infrared Imager/Radiometer Suite (VIIRS) that will be part of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory Project (NPP) missions. These and other products and data are described in greater detail in the following section.

Table 1. CREWS DST requirements and NASA remote sensing input match.

Parameter	CREWS DST Requirements (desired)	NASA Capability	Comments
1. Sea Surface Temperature (SST)	S: 1 km T: •24 hrs A: 0.5 K	**MODIS/Aqua & Terra** S: 1 km T: 2 days A: ±0.3 K	MODIS SST meets or exceeds the CREWS DST requirements.
2. Photosynthetically Available Radiation (PAR)	S: 1 km T: •24 hrs A: under evaluation	**MODIS/Aqua** S: 1 km T: 24 hrs A: uncertain	MODIS product is IPAR, which needs to be related to PAR. The accuracy of this MODIS product in coral reef regions is uncertain.
3. Wind Speed and Direction	S: •25 km T: •24 hrs A: 2 m/s or less, 20° or less	**SeaWinds/QuikSCAT** S: 25 km T: 24 hrs A: ±2 m/s, ±20°	The accuracy of this product is uncertain near land masses such as coral reefs and coastlines. Latency for SeaWinds products is 3 days (product available to user after 3 days).
4. Chromophoric Dissolved Organic Matter (CDOM)	S: 1 km T: •24 hrs A: under evaluation	**MODIS/Aqua** S: 1 km T: 24 hrs A: uncertain	Absorption coefficient of CDOM is estimated at 400 nm (m^{-1}). The accuracy of this MODIS product in coral reef regions is uncertain.
5. Chlorophyll Concentration	S: 1 km T: •24 hrs accuracy: under evaluation	**MODIS/Aqua** S: 1 km T: 24 hrs A: uncertain	The accuracy of this MODIS product in coral reef regions is uncertain.
6. Oceanic Rainfall	S: 0.25° T: 24 hrs A: under evaluation	**PR & TMI/TRMM** S: 1° T: 24 hrs A: uncertain	The use of rainfall data in CREWS DST is related to its effect on salinity and is presently under evaluation. The accuracy of the rainfall rate product from TRMM is uncertain. Latency for TRMM daily product is variable (10–30 days).
7. Sea Surface Height Anomaly (SSHA)	S: under evaluation T: under evaluation A: under evaluation	**Altimetry/Jason-1** S: along-track gridded T: 10 days A: 4.2 cms	The use of SSHA data in CREWS is presently under evaluation. It provides information on ocean circulation and will be applicable to ocean circulation models.
8. Surface Reflectance (Level 1B)	S: under evaluation T: daily A: uncertain	**MODIS product** S: 250 & 500 m T: 2 days A: uncertain **ASTER product** S: 15 m, VIS/NIR S: 30 m, NIR/SWIR T: on request (7 days) A: uncertain **Landsat product** S: 15 & 30 m T: 1–3 weeks A: uncertain	Landsat data has been useful in change detection and morphological studies of coral reefs. Similar application for the MODIS and ASTER reflectance data is possible.
9. Sea Surface Salinity (SSS)	S: 1 km T: daily A: 0.1 psu	**Aquarius (2007)** S: 100 km T: monthly A: 0.2–0.3 psu	SSS is important in water cycle studies (e.g., rainfall, river outflow) and for ocean currents and circulation models. The applicability of SSS from Aquarius to CREWS needs further evaluation.
10. Ocean Color and SST	Specifications as defined in items 1, 2, 4, and 5.	**VIIRS (2006)** S: 0.65 km T: daily A: same as MODIS	VIIRS will be the follow-on to the MODIS sensor. Its higher spatial resolution will enhance coral reef studies and the CREWS DST.

Table 2. Potential CREWS DST Model requirements and NASA input match.

Model Type and Level of NASA Support	CREWS DST Requirements (Desired)	Key Model Inputs	CREWS Relevant Model Outputs (Nowcast and Forecast)
1. Ocean General Circulation Model (OGCM); NASA Jet Propulsion Laboratory contribution to model development	SST, salinity (nowcast, forecast)	Atmospheric forcing data (from numerical weather prediction models; e.g., wind, pressure, air temp, evaporation/ precipitation)	Sea temperature and salinity at different depths
2. MIT General Circulation Model (MITgcm) (NASA-funded University research)	SST, salinity (nowcast, forecast)	Atmospheric forcing data. Also uses remote sensing SST, wind, and SSHA.	Sea temperature and salinity at different depths

3.3 Detailed Description of NASA Inputs to Improve CREWS DST

The CREWS DST can be enhanced through various NASA products and datasets listed in Table 1 and Table 2. Various products and datasets from instruments onboard the Aqua and Terra satellites (such as MODIS and ASTER), from SeaWinds onboard QuikSCAT, and from future satellites would be useful for the CREWS DST.

3.3.1 MODIS Products (Terra and Aqua)

At the present time, SST products are being generated from both Terra and Aqua, while the ocean color products (e.g., chlorophyll, IPAR) are being generated only from MODIS onboard Aqua as Level 2 and Level 3 data products. The Level 2 data product has daily coverage with a 1-km resolution at nadir for cloud-free pixels. This is the highest spatial resolution pixel size and is determined by the technical characteristics of the MODIS instrument (http://modis.gsfc.nasa.gov/about/specs.html). Level 2 data products are measurements of the bio-geophysical properties of the ocean and are derived from lower-level data via algorithm application. The constraints are that only cloud-free pixels are used (with sun glitter below a specified threshold) and that all valid pixels are outside a distance threshold from land. These product files cover a 5-minute interval and consist of 1354 pixels (2330 km) across track and 2030 pixels (2030 km at nadir) along track. The data are stored in Hierarchical Data Format (HDF-EOS) with each file containing 5 minutes of data. Level 3 products are associated with daily, 8-day (or weekly), and monthly data with 4.6-km, 36-km, or 1-degree spatial resolution. These higher-level products with lower resolution are derived by space- and time-binning of the Level 2 data products. The MODIS sensor on Aqua is ensuring continuity and a follow-on system in place before the older system on Terra is retired.

Sea Surface Temperature: MODIS has a number of infrared bands in the mid- and thermal-infrared that are used to optimize sea surface temperature determinations. The MODIS (Terra and Aqua) Level 2 sea surface temperature product provides two SST estimates for the same satellite pass using thermal-IR (11-12 µm, SST) and mid-IR (3-4 µm, SST4) wavebands. SST estimates are available at 1-km resolution and accuracy of better than 0.5°C over the global oceans. Day and night retrievals are provided as separate products for both SST and SST4 in degrees Celsius. SST is the most important parameter utilized by the CREWS network in generating coral reef bleaching alerts. MODIS SST inputs from Terra and Aqua would thus be an important enhancement to the CREWS DST. Pros/Cons: MODIS has a larger number of spectral channels than the AVHRR sensor, allowing for better estimates of SST and better cloud detection algorithms. The 11 µm (SST) and the 4 µm (SST4) SST products from Aqua have been validated by the MODIS product scientist(s). The accuracy of MODIS SST (0.3–0.5°C) is better than AVHRR SST estimates. The main disadvantage of the MODIS SST estimates is the daytime contamination of the ocean signal (mainly for the mid-IR bands) by the reflected solar radiation. As such, nighttime measurements are more accurate than daytime measurements. Although the use of both daytime and nighttime SST measurements would provide four daily measurements for CREWS, the applicability of daytime measurements would need to be evaluated in view of its degraded accuracy. The higher accuracy of the MODIS SST over the AVHRR SST provides an important incentive for its potential use in CREWS; however, the MODIS SST has not yet been applied to coral reef applications.

Instantaneous Photosynthetically Available Radiation (IPAR): The IPAR product provides an estimate of the amount of visible light available for photosynthesis. The product is called “instantaneous” because it is a measure of PAR only in the instant that the sensor views a given pixel and thus does not represent the irradiance averaged over the entire day. The CREWS expert system presently uses the daily PAR parameter in generating coral bleaching reports. The availability of the daily field PAR value at the CREWS station provides an opportunity to relate the MODIS IPAR product to PAR. Pros/Cons: The MODIS IPAR product can potentially provide an important input to the CREWS DST. However, IPAR must be related to the PAR parameter presently used by CREWS in generating its bleaching alerts. Also, IPAR has been developed and evaluated mainly for oceanic waters. In coastal and coral reef regions, bottom reflectance can seriously affect the accuracy of ocean color products generated by bio-optical algorithms (D’Sa et al., 2002) and the use of the IPAR product may need to be evaluated for different coral reef locations on a case-by-case basis. For example, use of a deep-water IPAR value may need to be evaluated as a substitute for use of a shallow-water value. A literature review has indicated that this product has not yet been used for coral reef applications.

CDOM Absorption Coefficient: The MODIS CDOM absorption product is being estimated using a semianalytic algorithm and provides the absorption coefficient of the chromophoric dissolved organic component at 400 nm waveband. However, at present the CREWS DST is not using this parameter when generating any alerts. Pros/Cons: High concentrations of CDOM can reduce the damaging effects of ultraviolet radiation on corals. This MODIS product can therefore be an important parameter in extending the use of field and remote sensing data to the CREWS DST. The accuracy of this product in coral reef regions is uncertain and would need to be evaluated. For example, a comparison of satellite-derived and field data in Florida Bay (D’Sa et al., 2002) has shown CDOM absorption to be underestimated by a factor of two to four. Bio-optical studies of CDOM absorption of the type conducted in coastal waters (D’Sa and Miller, 2003) and extended to coral reef regions would be useful in validating and improving estimates in the optically complex coral reef waters.

Chlorophyll Concentrations: The MODIS chlorophyll concentrations are estimated using both empirical and semianalytic algorithms and have been shown to give good estimates for oceanic waters. At present the CREWS DST is not using this parameter when generating any alerts. Pros/Cons: Chlorophyll is an important parameter for determining the water quality in coral reef regions. Elevated concentrations of chlorophyll could be due to high nutrients associated with sewage outflow or anthropogenic effects. Accurate MODIS estimates of this parameter could help reef managers initiate mitigation efforts. However, as previously indicated, the accuracy of ocean color products in coastal and coral reef regions are affected by various factors that include bottom reflectance, suspended sediments, and the presence of elevated CDOM. The applicability of this product for CREWS needs to be evaluated.

3.3.2 SeaWinds Products (QuikSCAT)

The SeaWinds radar instrument was launched onboard QuikSCAT on June 19, 1999, and has since been measuring winds over approximately 90 percent of the ice-free oceans on a daily basis. The SeaWinds instrument is a specialized microwave radar that measures near-surface wind speed and direction under all weather and cloud conditions over Earth's oceans.

Wind Speed and Direction: Wind products from SeaWinds are available daily at 25-km spatial resolution. The wind speed and direction accuracy are 2m/s and 20°, respectively. Other SeaWinds Level 3 daily products that can be downloaded from the NASA Distributed Active Archive Center (DAAC) (http://podaac.jpl.nasa.gov/quikscat/) consist of gridded values of scalar wind speed, meridional and zonal components of wind velocity, wind speed squared, and time given in fraction of a day. Rain probability determined using the Multidimensional Histogram Rain Flagging technique is also included as an indicator of wind values that may have degraded accuracy because of the presence of rain. Several additional Level 3 products have been produced by members of the SeaWinds on QuikSCAT Science Working Team. Many of these products provide the QuikSCAT data on coarser grids (0.5º or 1º), at smaller time intervals (6- or 12-hour maps), and use advanced interpolation techniques to fill gaps in the wind fields. Pros/Cons: Wind speed and direction is an important parameter used by the CREWS DST in generating the bleaching alerts. Wind speed provides an indication of sea state at the CREWS station. The CREWS expert system uses information on sea state in conjunction with PAR values to determine the level of coral reef exposure to damaging sunlight. Availability of this NASA product to CREWS would be an important enhancement to this DST. However, wind estimates near the land masses are not accurate and the distance for a valid wind product from a coral reef will need to be determined. A major concern is the future availability of wind data from QuikSCAT because the satellite is operating past its design life of 3 years. The follow-on SeaWinds sensor aboard the Japanese satellite Midori-2 stopped transmitting data when the satellite irrecoverably lost power. Ocean wind data is currently available from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) onboard Aqua. However, because this product contains only wind speed and no direction component, its applicability for CREWS will need further evaluation.

3.3.3 PR and TMI Products (TRMM)

The TRMM satellite, a joint project between the United States and Japan, was launched into a low Earth orbit in 1997. The three sensors aboard TRMM that are relevant for obtaining rainfall estimates are 1) Precipitation Radar, 2) the 9-channel passive microwave imager (the TMI), and the AVHRR-like visible-infrared radiometer (the VIRS). The PR measures the echo backscattered from rain; the strength of the echo is roughly proportional to the square of the volume of falling rain. Therefore the PR produces a very accurate estimate of rain profiles. The TMI measures the microwave radiation emitted by the Earth's surface and by clouds and rain drops. Because large ice particles (often present in upper cloud regions) tend to scatter the emitted radiation, the TMI uses its various channels, along with cloud models, to discriminate between these processes and to quantify the rain and ice responsible for the observed microwave signatures. One of the main challenges in obtaining estimates of rainfall rate from the TRMM has been to develop algorithms that can translate the electromagnetic measurements obtained from the PR, TMI, and VIRS instruments together into estimates of the instantaneous rain rate profiles.

Rainfall: Rainfall products using different algorithms and combinations of sensors are now being generated at the DAAC (GSFC). It appears that the daily and monthly 1º x 1º spatial resolution rainfall products would potentially be useful for CREWS. The accuracy of the rainfall product is at this time uncertain. Pros/Cons: Rainfall in oceanic waters affects salinity. Large changes in salinity can potentially affect coral growth. However, at this time CREWS is not using rainfall information in its expert system, and CREWS' spatial and accuracy requirements could be assessed at a future time. Large uncertainties exist on the accuracy of rainfall rates because it is affected by false radar echoes, by topography, and by the different ways that convection and precipitation can exist.

3.3.4 Altimeter Products (Jason-1)

The Jason-1 satellite was launched in December 2001 as a successor to the highly successful TOPEX/Poseidon mission that has been measuring ocean topography since 1992. Its primary mission was to collect oceanic surface height data. The Jason-1 satellite carries a dual-frequency radar altimeter (Poseidon-2), the Jason Microwave Radiometer, a tracking system receiver, a laser retroreflecor array, and a Global Positioning System (GPS) receiver. The instruments on board the satellite make observations of altimeter range, significant wave height, ocean radar backscatter cross-section (a measure of wind speed), ionospheric electron content (derived by a simple formula), tropospheric water content, and position relative to the GPS satellite constellation. Sea surface height data are derived from these altimeter measurements.

Sea Surface Height Anomalies (SSHA): Data are available along-track from NASA Jet Propulsion Laboratory (JPL) daily or at 10-day temporal resolution. Along-track gridded SSHA are available only at 10-day temporal resolution and consist of data values interpolated to a reference track of standard latitude and longitude locations that are common to every cycle allowing for a direct cycle–by-cycle comparison. In this case, ionospheric correction for each data point has been replaced by a 100-km along-track ionosphere. Pros/Cons: Estimates of SSHA from Jason-1 and TOPEX/Poseidon have been useful in weather prediction, ocean circulation, and sea-level height determination. SSHA data have also been useful as inputs to ocean circulation models, such as OGCM and MITgcm. Effects of sea-level rise and changes in ocean circulation on coral reefs are active research topics, and the SSHA data are important in providing monitoring data to resource managers. This product has not yet been applied for coral reef applications.

3.3.5 Sea Surface Salinity (SSS) from Aquarius

Aquarius is a planned NASA Earth System Science Pathfinder mission that will be carried out in partnership with the Argentine space commission to study the impact of the global water cycle on the ocean. The measurement objective is sea surface salinity, which describes the concentration of freshwater at the ocean's surface. Beginning in 2009, the Aquarius satellite mission will provide monthly global SSS maps over a period of three years. The satellite will carry three L-band radiometers (1.413 GHz) that are sensitive to salinity and a scatterometer that corrects for the ocean's surface roughness. The Aquarius measurement goals are 0.2 practical salinity units accuracy, 100 km spatial resolution, every month. Pros/Cons: In addition to SST, coral reefs are also sensitive to changes in salinity. The ability to measure salinity from space and its integration into the CREWS network could be an important enhancement to CREWS. Salinity is also an important input to ocean circulation models, and the assimilation of satellite-derived SSS into these models will greatly improve the capability to forecast ocean circulation and SST. However, the data stream from this satellite is not expected for at least another five years. Also, the utility of its large spatial (100 km) and temporal (monthly) resolution for CREWS is at present uncertain.

3.3.6 Ocean Color and SST on VIIRS

VIIRS: The Visible/Infrared Imager/Radiometer Suite will combine the radiometric accuracy of the AVHRR currently flown on the NOAA polar orbiters with the moderate (0.65 km) spatial resolution of the Operational Linescan System flown on the Defense Meteorological Satellite Program spacecraft. VIIRS will contain multiple visible and infrared channels between 0.3 and 14 μm. Pros/Cons: VIIRS will provide capabilities to produce higher resolution and more accurate measurements of SST than are currently available from the heritage AVHRR instruments and will provide the operational capability for ocean color observations and for a variety of derived ocean color products. Data products from VIIRS will potentially enhance the future satellite requirements for the CREWS network. However, the data stream from this sensor is not expected to be available for at least another three years.

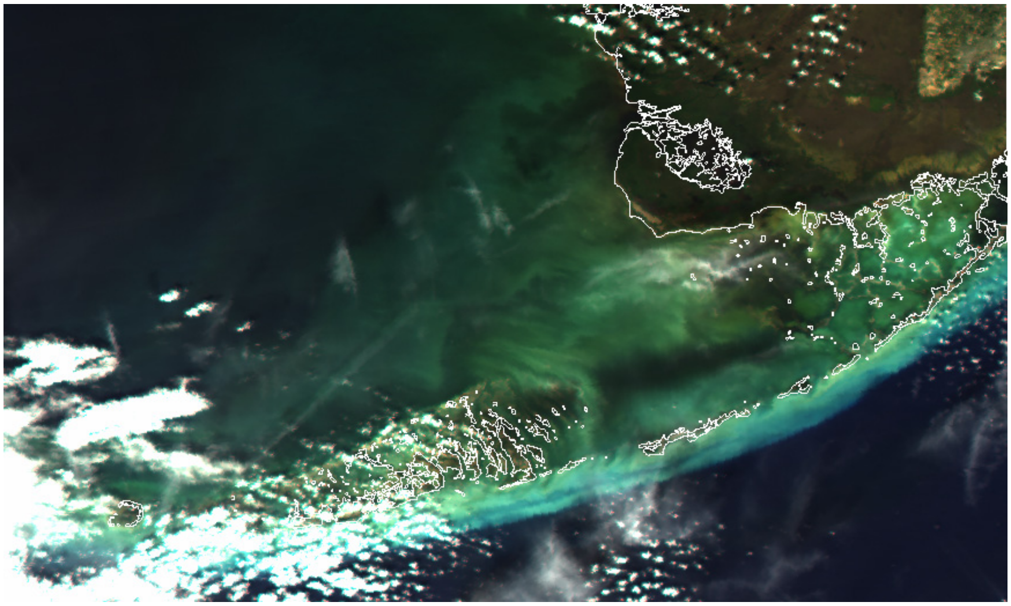
3.3.7 Other Moderate Resolution Earth Science Data

Preliminary evaluation suggests that a number of other Earth science datasets (Table 2, number 1) may be useful in enhancing the CREWS DST. Of these, the Landsat spectral radiance data have been applied for change detection and morphological studies of coral reefs. Other moderate resolution reflectance data include the 250 and 500 m MODIS and the ASTER data.

Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data: The Landsat 7 ETM+ Earth observing instrument replicates the highly successful Thematic Mapper instruments onboard Landsat 4 and 5. The ETM+ is a multispectral scanning radiometer that provides image data in 8 spectral bands. Spatial resolution for the visible and near-infrared (bands 1-5 and 7) is 30 meters and for the thermal infrared (band 6) is 60 meters. Resolution for the panchromatic (band 8) is 15 meters. The approximate scene size is 170 x 183 kilometers. ETM+ data products are available at various levels of processing (http://landsat7.usgs.gov/programnews.html), with the Level 1G products being previously used for coral reef research applications (e.g., mapping). The Level 1G product includes both radiometric and geometric corrected image data provided in rescaled 8-bit (digital number) values. The scene will be rotated, aligned, and georeferenced to a user-defined map projection. Geometric accuracy of the systematically corrected product should be within 250 meters for low-relief areas at sea level. ETM+ achieves global coverage with a 16-day repeating ground track. Standard data latency is 1–3 weeks. Pros/Cons: The CREWS DST is at present not utilizing any high-resolution image data in generating its bleaching alerts. Also with the recent degradation of the ETM+ sensor (the scan line corrector on the Landsat 7 ETM+ instrument failed on May 31, 2003), its utility for coral reef applications remains uncertain at this time.

MODIS 250- and 500-m data: The MODIS (2 channels at 250 m and 5 channels at 500 m) moderate resolution data products from Terra and Aqua are specifically land products (e.g., surface reflectance, vegetation indices). The MODIS 250-m spatial resolution data are available in two bands and have large spectral bandwidths (620–670 nm and 841–876 nm).

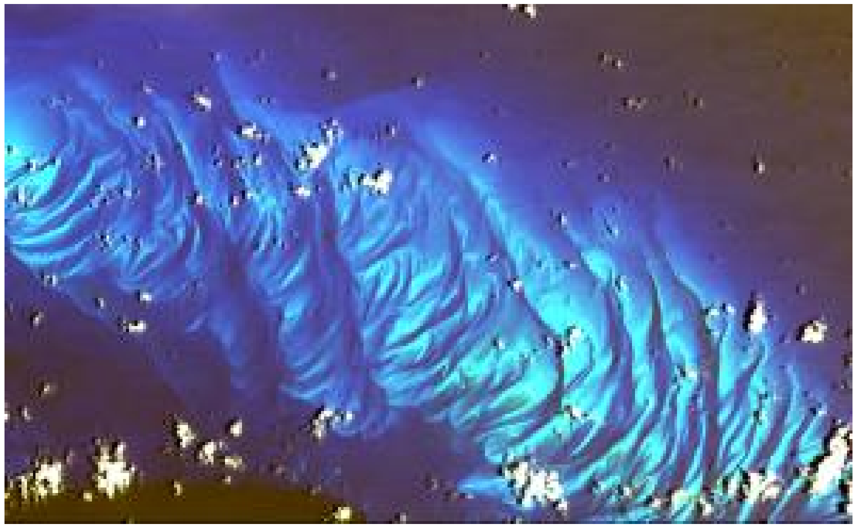
Pros/Cons: The CREWS DST presently does not incorporate moderate resolution satellite images for generating bleaching alerts because of the limitation of the expert system. However, the proposed migration to the G2 expert system will allow the incorporation and use of satellite images into its DST. The MODIS 250-m and 500-m datasets may then potentially be useful in detecting the onset of bleaching events (Figure 14). A recent application of the MODIS 250 m dataset has been found useful in determining suspended sediments in coastal waters (Miller and McKee, 2004). An extension of this work to determine suspended sediment concentrations in coral reef regions would be an excellent enhancement to the CREWS DST. High concentrations of suspended sediments have been shown to adversely affect coral growth rates (Miller and Cruise, 1995) by reducing light availability and the siltation of the sediment particles on the corals. Detection of elevated estimates of suspended sediments can be used to initiate mitigation efforts to reduce their concentration. However, the applicability of these products for coral reef regions and CREWS needs further evaluation and assessment.



Source: http://modis.marine.usf.edu/index.html

Figure 14. A 500-m resolution image of Florida Bay coral reef system from the MODIS sensor. Fine details on coral reef morphology are still discernible at this resolution.

ASTER data: The ASTER instrument onboard Terra obtains high-resolution images at 14 different wavelengths from the visible to the thermal infrared (TIR). Products generated from ASTER are geared mainly toward land applications. Unlike other instruments aboard Terra, ASTER does not collect data continuously; rather it collects an average of 8 minutes of data per orbit. ASTER collects about 600 pictures ("scenes") a day, each covering about 60 x 60 km. The system can reproduce all Landsat bands. ASTER uses three telescopes to acquire data in the visible and near-infrared (VNIR; 15-m spatial resolution), short-wave infrared (SWIR; 30-m spatial resolution), and TIR (90-m spatial resolution). Pros/Cons: Potential application of ASTER data for coral reefs may be restricted to only the three VNIR channels (520–600 nm, 630–690 nm, and 780–860 nm), which are available on request. The nominal ASTER data latency is 7 days (through the USGS EROS Data Center), although this timeframe is not guaranteed. A high-resolution image from ASTER of the Bahamas coral reefs (Figure 15) shows many reef features. Such features could be monitored for change detection (e.g., onset and appearance of bleaching) that could potentially be useful for CREWS.



Source: http://asterweb.jpl.nasa.gov/gallery/

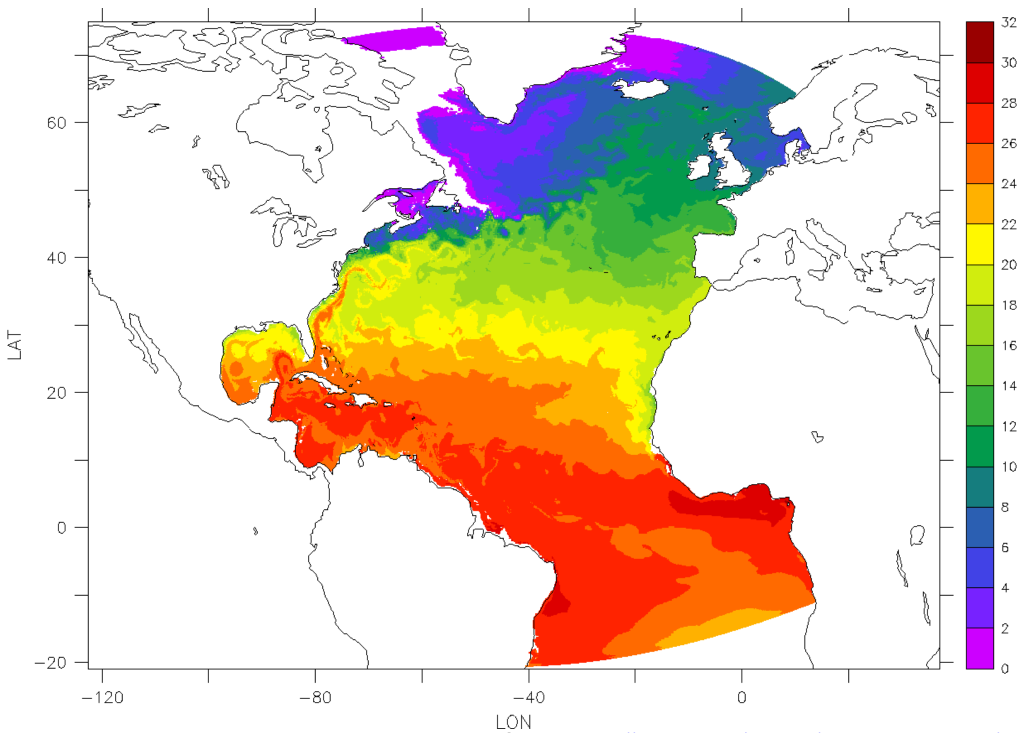
Figure 15. An ASTER image of the Bahamas coral reefs. The areas that look like folded material are carbonate sand dunes in the shallow waters of Tarpun Bay, in the Bahamas. The sand making up the dunes comes from the erosion of limestone coral reefs and has been shaped into dunes by ocean currents. The image was acquired on May 12, 2002, and covers an area of 28.2 x 46.1 km.

(Credit for these images to NASA/GSFC/METI/ERSDAC/JAROS, and U.S/Japan ASTER Science Team).

3.3.8 NASA Supported Hydrodynamic Models

JPL OGCM: The OGCM is based on the Parallel Ocean Program developed at Los Alamos National Laboratory and evolved from the Bryan-Cox 3-dimensional primitive equations ocean model developed at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL), and later known as the Semtner and Chervin model (Semtner and Chervin, 1992) or the Modular Ocean Model (MOM). Currently, there are hundreds of users within the so-called Bryan-Cox ocean model family, making it the dominant OGCM code in the climate research community. The OGCM solves the 3-dimensinal primitive equations with the finite difference technique and parallelizes very well on massively parallel computers. The new JPL OGCM ocean model has significantly optimized the original code and has user-friendly features that couples well with atmospheric or biogeochemical models. One of the principal roles of the ocean in the global heat balance is storage of heat, which moderates seasonal extremes and leads to the contrast in temperatures between the ocean and continents. Ocean models such as the JPL OGCM contribute to understanding the current climatic conditions and predicting future climate change through their ability to nowcast or forecast oceanic conditions, such as sea temperature, salinity, and currents. Main inputs to the JPL OGCM are the atmospheric forcing data, such as winds, pressure, air temperature, and evaporation/precipitation. Some outputs of the JPL OGCM model of interest to CREWS include sea temperature, salinity, ocean circulation, and sea surface height. As an initial step, the nowcast model outputs of salinity and temperature should be validated against the CREWS field data. Based on these results, the model outputs could be used for coral regions that have no field stations. Pros/Cons: An important advantage of models such as JPL OGCM over remote sensing data is their ability to model oceanic conditions of temperature and salinity over various water depths, which is particularly relevant for CREWS because coral reefs are found at various depths and model outputs can be used to predict bleaching events for corals that are located at various depths below the sea surface. Additionally, the prediction capability of the OGCM model (e.g., El Niño events) could allow bleaching probabilities to be forecast. While at present no mitigation strategies have been developed, a better understanding of coral reef physiology could allow such strategies to be available in the future. An important application of such remote sensing data as SST (MODIS) and SSH (Jason-1) has been its use as input to the models or its ability to assess the performance of the models. The application of the OGCM model for specific coral reef regions have not been documented, although there are benefits to integrating them into DSTs such as CREWS (e.g., nowcast of temperature at different depths).

MIT Global Circulation Model (MITgcm): MITgcm is a 3-D ocean circulation model developed by MIT researchers on the basis of GFDL MOM3 that incorporates new advancements in physics and computing technology. MITgcm has a single dynamical kernel that can drive forward either oceanic or atmospheric simulations. Its non-hydrostatic capability can be used to study both small-scale (e.g., convection) and large-scale (e.g., global circulation patterns) processes. The model provides support for treatment of irregular geometries has been used to model a wide range of phenomena, from convection on the scale of meters in the ocean to the global pattern of atmospheric winds. The capability of the MITgcm model to execute at high resolution (e.g., 1/6° horizontal resolution and 21 vertical levels) allows it to resolve the ubiquitous oceanic eddies (Figure 16).



Source: http://mitgcm.org/sealion/online_documents/node6.html

Figure 16. Instantaneous temperature map from a 1/6° simulation of the North Atlantic. The figure shows the temperature in the second layer (37.5 m depth).

The MITgcm ocean model is driven with an atmospheric forcing variable, such as mean winds along with boundary conditions on temperature and salinity at the surface. The transfer properties of ocean eddies, convection, and mixing can also be parameterized in this model. The simulated output includes 3-D oceanic currents, sea temperature, and salinity fields for various depths. NASA and the Office of Naval Research are funding a consortium of scientists at NASA JPL, the Massachussetts Institute of Technology, and the Scripps Institute of Oceanography whose goal is to bring the ocean state estimation from its current experimental status to that of a practical and quasi-operational tool for studying large-scale ocean dynamics based on the MITgcm model. Transition of the MITgcm model to a quasi-operational state will be of benefit to CREWS by making available nowcast and forecast estimates of sea temperature and salinity for generating coral bleaching alerts. As a first step, the nowcast output estimates of temperature and salinity at various depths could be compared against the daily CREWS field data for validation purposes. Pros/Cons: The ability of the MITgcm model to treat non-hydrostatic dynamics in the presence of complex geometry makes it a potentially important tool to study and forecast events (e.g., surface and subsurface temperatures, salinity, and sea surface height) in coral reef regions. Such applications are only now appearing in literature. For example, the MITgcm has been combined with a dual Kalman filter and the assimilation of SST (MODIS) and altimeter (Jason-1) remote sensing data to obtain insight into the upper ocean subsurface thermal structure and associated stress on coral reefs (Fuckar et al., 2004). Integrating the outputs of the MITgcm model with CREWS could enable the DST to provide model validation along with nowcasting and forecasting capability for coral health (e.g., bleaching). However, the MITgcm model has not been used on an operational basis to generate outputs that could be useful to the CREWS DST.

4.0 Conclusions and Recommendations

4.1 Findings

- NOAA's Coral Reef Early Warning System is a network of *in situ* monitoring stations at strategic coral reef areas that establishes long-term datasets to provide near-real-time information products (e.g., bleaching alerts) and surface-truthing NOAA satellite SST.
- At present, CREWS does not use any NASA Earth science data in its DST. Three NASA products (SST, IPAR, and Winds) could be directly useful to the CREWS DST. However, these products need to be evaluated or validated for coral reef regions.
- At present CREWS does not use any NASA-supported ocean circulation models that generate nowcast or forecast of sea temperature or salinity outputs. These model outputs have not been evaluated or validated for coral reef regions.
- The DST is still in its early stages and is being used as a research tool for providing field data to researchers who use it to improve the expert-based decision system. The integration of NASA ESE data and products into the CREWS network is timely and should be explored and coordinated with the NOAA partners.
- NASA support to the CREWS DST will represent a major step toward the Oceans.US recommendation to find ways to truly integrate data such as the NASA remote sensing data and products in an integrated manner.

4.2 Recommendations

- The recommended NASA products with the highest potential for immediate applicability to the CREWS DST are 1) SST, and 2) Wind Speed and Direction. Integration and verification/validation of these products within the CREWS environment should be pursued in the near term. The MODIS SST product can be directly validated with the CREWS SST field data. The V&V of the wind data from SeaWinds onboard QuikSCAT will involve numerous steps, the most immediate of which are a) identifying the most suitable wind pixel that is not contaminated by land mass and, b) correlating the valid wind value with the CREWS station wind and speed.
- The MODIS IPAR product has the next highest potential for addressing the CREWS DST needs. The IPAR product gives a measure of instantaneous photosynthetically available radiation. However, CREWS uses the daily integrated available radiation. The MODIS IPAR product needs to be related to PAR so that it can be useful to the DST.
- Additional recommended products with good potential for enhancing the CREWS DST effort in monitoring coral reef health are 1) chlorophyll concentration, and 2) CDOM absorption. Accurate

estimates of these products around coral reef sites other than at CREWS station locations could allow mitigation strategies to be initiated (e.g., control of pollution point sources). It is recommended that as part of the validation and verification phase, these products be validated through field measurements of these parameters at the coral reef sites (Hochberg and Atkinson, 2000; Hall and Miller, 2002; D'Sa et al., 2002; D'Sa and Miller, 2003).

- Several moderate resolution reflectance products (MODIS 250 and 500 m; ASTER) have the potential to enhance the CREWS DST. Many of these products are still being evaluated for oceanographic applications and have not been used for coral reef regions. As these evaluations progress, NASA should work more closely with CREWS and various researchers to validate these products against CREWS needs.
- Further study on the use of other NASA contributions should begin. The integration of NASA remote sensing products and outputs from hydrodynamic models into the CREWS data stream will require an in-depth analysis of the CREWS system, its data formatting needs, and compatibility with NASA data formats.
- A number of unresolved issues exist on the use of NASA data products and models to enhance the CREWS DST. While a telecon with the CREWS management clarified some of those uncertainties, it is recommended that the additional in-depth discussions be conducted by the NASA CREWS evaluation team and CREWS personnel.

4.3 Next Steps

If the Coastal Management team decides to provide with the V&V phase, then the following steps should potentially be followed:

- Using its systems engineering capabilities, NASA must collaborate with NOAA to review the results of this CREWS evaluation and must jointly refine and validate the requirements listed here to ensure they match CREWS needs and will enable CREWS mission success.
- Briefly, key issues to be addressed following the evaluation phase are the V&V of the NASA Earth science remote sensing data and the outputs of NASA-supported ocean circulation models that have been discussed in greater detail in the previous sections.
- Other immediate steps in the evaluation phase are to select and prioritize the NASA contributions (various relevant products) to the CREWS DST and to proceed with the integration, verification, and validation of those NASA contributions within the CREWS environment.

In Figure 17, the DST V&V paradigm is shown as a pyramid with the idea that V&V of a DST must take place from the ground up. This V&V paradigm should be applied to potential enhancements of the CREWS DST. V&V should start with the "data and product characterization" level. This level can also be described as "observations." At this level, many individual pieces need to be validated and characterized for coral reef regions:

- MODIS Standard Products (e.g., SST, IPAR, chlorophyll, CDOM absorption)
- Wind products from SeaWinds onboard QuikSCAT
- Sea Surface Height Anomaly product from Jason-1
- MODIS 250 m and 500 m reflectance products
- MODIS Decadal Products

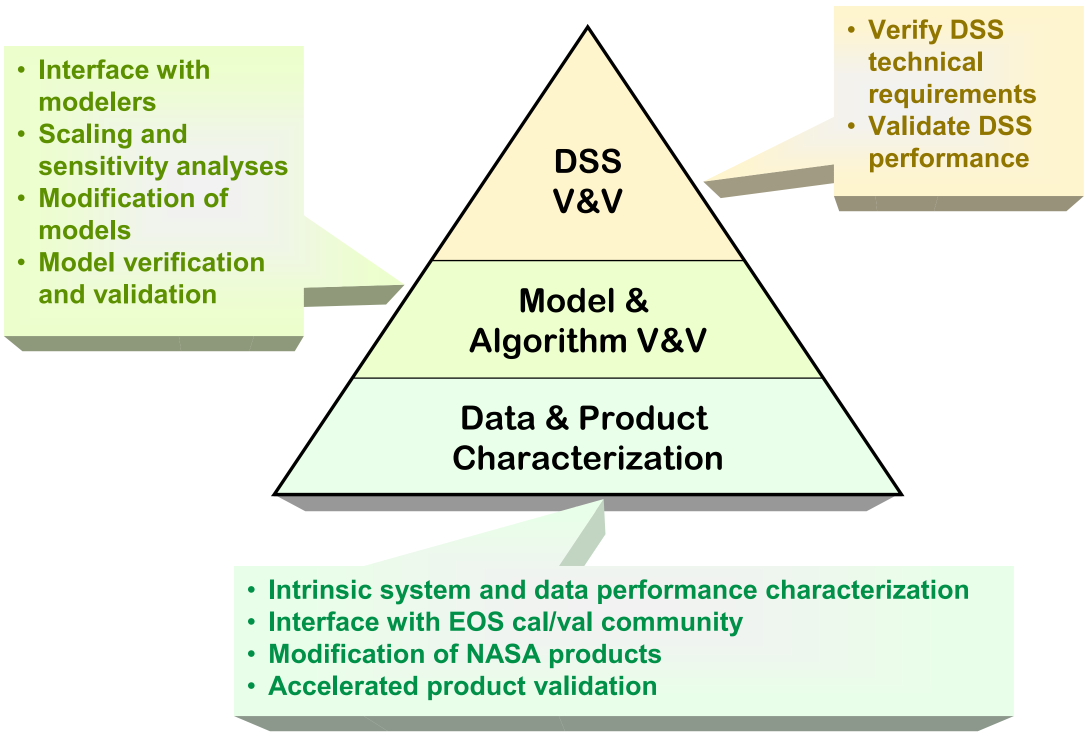


Figure 17. V&V hierarchy.

The responsibility for V&V of the individual elements of the DST enhancement is dispersed. The responsibility for V&V of MODIS Standard Products lies with the original product developers in the MODIS Ocean team. The responsibility for the MODIS 250-m data lies with a validation team at NASA. The GSFC-led team has responsibility for the MODIS Decadal Products. However, these teams have not yet validated the various products for coral reef monitoring.

There is a critical need for additional evaluation and validation of the NASA Earth science products and data for the CREWS application because coral reef regions present difficulties in interpretation of both optical and microwave remote sensing signals. Also, because CREWS information needs are time sensitive, one of the key activities will be V&V of latency or delivery time. Furthermore, if NASA and NOAA agree to evaluate any additional enhancements, the NASA Coastal Management application team should work these evaluations into the overall V&V plan.

The final assessment of an enhanced DST will actually be the benchmarking process that follows V&V stages (Figure 4), but as sub-components are added or upgraded, they may be assessed pre-benchmarking to determine if they contribute properly to the overall system.

5.0 References

Andréfouët, S., and C. Payri, 2000. Scaling-up carbon and carbonate metabolism of coral reefs using in-situ data and remote sensing. *Coral Reefs*, 19:259–269.

Andréfouët, S., A. Naseer, and B.G. Hatcher, 2002. Protocol for geomorphological mapping of Maldives coral reefs using Landsat satellite data. *University of South Florida/Dalhousie University*.

Andréfouët, S., F. Muller-Karger, E. Hochberg, C. Hu, and K. Carder, 2001. Change detection in shallow coral reef environments using Landsat 7 ETM+ data. *Remote Sensing of Environment*, 79:150–162.

Andréfouët, S., P. Kramer, D. Torres-Pulliza, K. E. Joyce, E. J. Hochberg, R. Garza-Pérez, P. J. Mumby, B. Riegl, H. Yamano, W. H. White, M. Zubia, J. C. Brock, S. R. Phinn, A. Naseer, B. G. Hatcher, and F. E. Muller-Karger, 2003. Multi-site evaluation of IKONOS data for classification of tropical coral reef environments. *Remote Sensing of Environment,* 88:128–143.

Atkinson, P. M., and P. J. Curran, 1997. Choosing an appropriate spatial resolution for remote sensing investigations. *Photogrammetric Engineering & Remote Sensing,* 63:1345–1351.

Bahill, A.T., and B. Gissing, 1998. Re-evaluating systems engineering concepts using systems thinking. *IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews*, 28:273–275.

D'Sa, E. J., C. Hu, F. E. Müller-Karger, and K. L. Carder, 2002. Estimation of colored dissolved organic matter and salinity fields in case 2 waters using SeaWiFS: Examples from Florida Bay and Florida Shelf. *Earth and Planetary Science (Indian Academy of Sciences),* 111:197–207.

D'Sa, E. J., and R. L. Miller, 2003. Bio-optical properties in waters influenced by the Mississippi River during low flow conditions. *Remote Sensing of Environment,* 84:538–549.

Fuckar, N. S., E. J. Baylor, and A. E. Strong, 2004. Ocean satellite and data assimilation montoring of heat stress conditions in coral reef ecosystems. In: *Proceedings AGU Ocean Sciences*, Portland, Oregon.

Gasch, J., T. Arvidson, S. N. Goward, S. Andréfouët, C. Hu, and F. E. Müller-Karger, 2000. An assessment of Landsat 7/ETM+ coverage of coral reefs worldwide. In *IEEE IGARSS 2000,* Honolulu, Hawaii.

Glynn, P. W., 1984. Widespread coral mortality and the 1982-83 El Nino warming event. *Environmental Conservation,* 11:133–146.

Glynn, P. W., 1993. Coral reef bleaching: ecological perspectives. *Coral Reefs,* 12:1–17.

Goreau, T. J., and R. M. Hayes, 1994. Coral bleaching and ocean 'hotspots'. *Ambio*., 23:176–180.

Hall, C. M., and R. L. Miller, 2002. The use of chlorophyll fluorescence lifetime to assess phytoplankton physiology within a river-dominated environment. *Seventh International Conference on Remote Sensing for Marine and Coastal Environments,* Miami, Florida.

Hendee, J. C., 1998. An expert system for marine environmental monitoring in the Florida Keys national marine sanctuary and Florida Bay. In: *Proceedings of the Second International Conference on Environmental Coastal Regions*, Southampton, pp. 57–66.

Hendee, J. C., E. Mueller, and T. Moore, 2001. A data-driven expert for producing coral bleaching alerts at Sombrero Reef in the Florida Keys. *Bulletin of Marine Science,* 69: 673–684.

Hendee, J., G. Liu, A. Strong, J. Sapper, D. Sasko and C. Dahlgren, 2002. Near real-time validation of satellite sea surface temperature products at rainbow gardens reef, Lee Stocking Island, Bahamas. *Seventh International Conference on Remote Sensing for Marine and Coastal Environments,* Miami, Florida.

Hoegh-Guldberg, O., 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research,* 50: 839–866.

Hochberg, E., and M. Atkinson, 2000. Spectral discrimination of coral reef benthic communities. *Coral Reefs,* 19:164–171.

Hughes, T. P., and J. H. Connell, 1999. Multiple stressors on coral reefs: a long-term perspective. *Limnology and Oceanography,* 444: 932–940.

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

Liu, G., J. E. Meyer, I. C. Guch, and M. A. Toscano, 2001. NOAA's satellite coral reef bleaching early warning products aimed at local reef sites around the globe. *Reef Encounter,* 30:10–13.

Marshall, P. A., and A. H. Baird,. 2000. Bleaching of corals on the Great Barrier reef: Differential susceptibilities among taxa. *Coral Reefs,* 19:155–63.

Miller, R. L., and J. F. Cruise, 1995. Effects of suspended sediments on coral growth: Evidence from remote sensing and hydrologic modeling. *Remote Sensing of Environment,* 53:177–187.

Miller, R. L., and B. A. McKee, 2004. Using MODIS Terra 250m imagery to map concentrations of total suspended matter in coastal waters. *Remote Sensing of Environment* (submitted).

National Aeronautics and Space Administration, 2004. *Scientific Data Purchase.* Earth Science Applications Directorate, John C. Space Center, http://www.esa.ssc.nasa.gov/datapurchase/default.aspx (accessed May 15, 2004).

National Oceanic and Atmospheric Administration, 2004. *CREWS Network: Near-Real-Time Data & Expert System Reports.* NOAA's Coral Health and Monitoring Program, Atlantic Oceanographic and Meteorological Laboratory, Office of Oceanic and Atmospheric Research, http://www.coral.noaa.gov/crw/real_data.shtml (accessed May 15, 2004).

Robinson, J. A., G. C. Feldman, N. Kuring, B. Franz, E. Green, M. Noordeloos, and R. P. Stumpf, 2000. Data fusion in coral reef mapping: Working at multiple scales with SeaWiFS and astronaut photography. *Proceedings of the 6th International Conference on Remote Sensing for Marine and Coastal Environments*, 2:473–483.

Semtner, A. J., and R. M. Chervin, 1992. Ocean-General Circulation from a global eddy-resolving model. *Journal of Geophysical Research,* 97:5493–5550.

Strong, A. E., C. S. Barrientos, C. Duda, and J. Sapper, 1997. Improved satellite techniques for monitoring coral reef bleaching. *Proceedings of the 8th International Coral Reef Symposium* 2:1495–1498.

Strong, A. E., T. J. Goreau, and R. Hayes, 1998. Ocean HotSpots and coral reef bleaching: January–July 1998. *Reef Encounters,* 24:20–22.

Stumpf, R. P., K. Holderied, J. A. Robinson, G. Feldman, and N. Kuring, 2003. Mapping water depths in clear water from space. *Proceedings of the 13[13th] Biennial Coastal Zone Conference,* Coastal Zone 03, July 13–17, Baltimore, Maryland, http://eol.jsc.nasa.gov/newsletter/CoastalZone (accessed May 17, 2004).

Toscano, M. A., G. Liu, I. C. Guch, K. S. Casey, A. E. Strong, and J. E. Meyer, 2001. Improved prediction of coral bleaching using high resolution HotSpot anomaly mapping. In: *Proceedings 9th International Coral Reef Symposium,* Bali, Indonesia.

Wilkinson, C., O. Linden, H. Cesar, G. Hodgson, J. Rubens, and A. E. Strong, 1999. Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: An ENSO impact and a warning of future change? *Ambio.,* 28:188–196.

Appendix A. Glossary

Benchmark – A standard by which a product can be measured or judged (i.e., How did the DST that assimilated NASA measurements compare in its operation, function, and performance to the earlier version). The benchmarking process is required to support adoption of innovative solutions into operational environments that affect life and property.

Decision Support System (DSS) – a computer based information-processing system for scenario optimization through multi-parametric analysis. A DST utilizes a knowledge base of information with a problem solving strategy that may routinely assimilate measurements and/or model predictions in support of the decision making process. The DST provides an interface to facilitate human inputs and to convey outputs. Outputs from a DST would typically be used for making decisions at the local level and outputs from multiple DSTs may be used in establishing policy.

Decision Support Tools (DSTs) – a suite of solutions owned by NASA partners that are used in a variety of problem domains for decision and policymaking. These solutions could include assessments, decision support systems, decision support calendars, etc.

Evaluation – Identify decision support tools (assessments and DSTs) that have been developed by Federal agencies and other partners that are a priority to citizens of our nation and that can be enhanced by NASA Earth science results. Develop the specifications for how the candidate DST can be augmented by assimilating NASA Earth science observations and predictions.

Validation – A process to ensure the completed products (software, algorithm, model) effectively serve the functional requirements.

Verification – A life cycle process to ensure the products being developed meet the stated specifications (functional, performance, and design).

Appendix B. Abbreviations and Acronyms

AMSR-E	Advanced Microwave Scanning Radiometer – EOS
AOML	Atlantic Oceanographic and Meteorological Laboratory
ASTER	Advanced Spaceborne Thermal Emission and Reflectance Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CDOM	Chromophoric Dissolved Organic Matter
CHAMP	Coral Health and Monitoring Program
CLIPS	C Language Integrated Production System
CRW	Coral Reef Watch
CREWS	Coral Reef Early Warning System
DAAC	Distributed Active Archive Center
DHW	Degree Heating Weeks
DSS	Decision Support System
DST	Decision Support Tool
EOS	Earth Observing System
ESA	Earth Science Applications
ETM+	Enhanced Thematic Mapper Plus
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
IPAR	Instantaneous Photosynthetically Available Radiation
IR	Infrared
MIT	Massachusetts Institute of Technology

MITgcm	MIT Global Circulation Model
MMM	Maximum Monthly Mean
MODIS	Moderate Resolution Imaging Spectroradiometer
MOM	Modular Ocean Model
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
OAR	(Office of) Oceanic and Atmospheric Research
OGCM	Ocean General Circulation Model
PAR	Photosynthetically Available Radiation
QuikSCAT	Quick Scatterometer
SeaWiFS	Sea-viewing Wide Field-of-View Sensor
SPOT	System Pour l'Observation de la Terre
SSC	Stennis Space Center
SSH	Sea Surface Height
SSHA	Sea Surface Height Anomaly
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SWIR	Short Wave Infrared
TIR	Thermal Infrared

TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
UVR	Ultraviolet Radiation
USGS	U.S. Geological Survey
V&V	Verification and Validation
VIIRS	Visible Infrared Imaging Radiometer Suite
VIRS	Visible Infrared Radiometer
VNIR	Visible Near Infrared

Appendix C. Relevant Earth Observing Missions and Sensors

Table C-1. Earth observing missions and sensors relevant to CREWS.

Visible-Infrared Sensors	Passive Microwave Sensors	Scatterometers
Parameters: SST, other	Parameters: Precipitation (future potential)	Parameters: Wind Speed, Direction, Sea Level
• MODIS, ASTER • Coral Reef Research Current Use: LANDSAT 5 & 7, AVHRR, SeaWiFS, IKONOS • MODIS Follow-On: NPOESS VIIRS	• TMI on TRMM, Aqua • CREWS Current Use: None • Operational Follow-On: NPOESS CMIS	• SeaWinds on QuikSCAT • Poseidon on Jason-1 • CREWS current use: None • Follow-On: Jason-2 (uncertain)

C.1. ASTER

ASTER

(Advanced Spaceborne Thermal Emission and Reflection Radiometer)

ASTER is a cooperative effort between NASA and Japan's Ministry of International Trade and Industry. It is the only high spatial resolution imaging instrument on the Terra platform. ASTER's ability to serve as a "zoom lens" for other instruments will be particularly important for change detection and calibration/validation studies. ASTER owes its heritage to Landsat's TM, MSS, and ETM+ instruments.

MISSION:

- Terra – Dec. 1999

PECAD USE:

- Sensor to be used as "gap filler" between Landsat missions.

PRODUCT SUMMARY:

- Detailed maps of land surface temperature, emissivity, reflectance, and elevation to better understand the interactions between the biosphere, hydrosphere, lithosphere, and atmosphere

VITAL FACTS:

- Four Subinstruments: VNIR – one nadir-looking, one rear-looking pushbroom; SWIR – one pushbroom; TIR – one whiskbroom
- Bands: 14 between 0.52 µm and 12.0 µm
- Spatial Resolution: VNIR - 15 m, SWIR - 30 m, TIR - 90 m
- Swath: 60 km at nadir, swath center is pointable across track 106 km (SWIR, TIR) and 314 km (VNIR)
- Repeat Time: Between 4 and 16 days
- Design Life: 5 years

OWNER:

- Japan, METI, NASA

LINK: http://asterweb.jpl.nasa.gov/

C.2. ETM+

ETM+

(Enhanced Thematic Mapper Plus)

The ETM+ instrument is an eight band multispectral scanning radiometer capable of providing high resolution imaging of the Earth's surface. ETM+ detects spectrally filtered radiation at visible, NIR, short-wave, and TIR frequency bands. ETM+ owes its heritage to Landsat's TM and ETM instruments.

MISSION:

- Landsat 7 – April 1999

PECAD USE:

- Currently used for VINs and moderately high resolution imagery

PRODUCT SUMMARY:

- Measures surface radiance and emittance, land cover state and change, and vegetation type

VITAL FACTS:

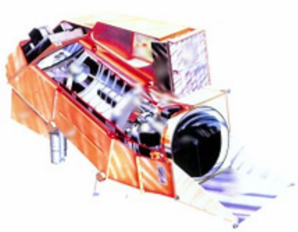
- Instrument: Whiskbroom multispectral scanning radiometer
- Bands: Bands one to five: 0.45-0.52 µm, 0.52-0.61 µm, 0.63-0.69 µm, 0.75-0.90 µm, 1.55-1.75 µm; band six: 10.40-12.5 µm; band seven: 2.09-2.35 µm; panchromatic: 0.52-0.90 µm
- Spatial Resolution: Bands one to five and seven: 30 m; band six: 60 m; panchromatic: 15 m
- Swath: 185 km
- Repeat Time: 16 days
- Design Life: 5 years

OWNER:

- U.S., NASA

FOLLOW-ON:

- ALI – EO-1



LINK: http://ls7pm3.gsfc.nasa.gov/Science.html

C.3. MODIS

MODIS

(Moderate Resolution Imaging Spectroradiometer)

MODIS on Terra and Aqua comprehensively measure ocean, land, and atmospheric processes over the entire Earth every 1 to 2 days from complementary orbits, acquiring data in 36 spectral bands and 3 different spatial resolutions. These data will improve our understanding of global Earth system dynamics and the interactions between land, ocean, and lower atmosphere processes. MODIS owes its heritage to POES AVHRR, NOAA's HIRS, and Landsat's TM instruments.

MISSIONS:

- Terra – Dec. 1999
- Aqua – May 2002

PECAD USE:

- Proposed use for VINs, surface reflectance, LAI, land surface temperature, land cover and snow cover
- Possible use for ET and primary production

PRODUCT SUMMARY:

- Measurements in 36 spectral bands for observations of high-priority global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere

VITAL FACTS:

- Instrument: Whiskbroom imaging radiometer
- Bands: 36 from 0.4 and 14.5 µm
- Spatial Resolution: 250 m, 500 m, and 1,000 m
- Swath: 2,330 km (across track) by 10 km (along track at nadir)
- Repeat Time: Global coverage in 1-2 days
- Design Life: 6 years

OWNER:

- U.S., NASA

FOLLOW-ON:

- VIIRS – NPOESS

LINK: http://modis.gsfc.nasa.gov/

C.4. VIIRS

VIIRS

(Visible Infrared Imaging Radiometer Suite)

VIIRS will collect visible/IR imagery and radiometric data. Data types will include atmospheric, clouds, Earth radiation budget, clear-air land/water surfaces, sea surface temperature, ocean color, and low light visible imagery. It will combine the radiometric accuracy of the AVHRR with the higher (0.65 km) spatial resolution of the Operational Linescan System flown on DMSP. VIIRS owes its heritage to Terra's MODIS, POES AVHRR, and ORBIMAGE's SeaWiFS instruments.

MISSIONS:

- NPP – 2006
- NPOESS – 2010

PRODUCT SUMMARY:

- Data types such as atmospheric, clouds, Earth radiation budget, clear-air land/water surfaces, sea surface temperature, ocean color, and low light visible imagery

OWNER:

- U.S., NOAA

PECAD USE:

- Planned as MODIS follow on for VINs and all other relevant products

VITAL FACTS:

- Instrument: Whiskbroom imaging radiometer
- Bands: 22 between 0.3 µm-14 µm
- Spatial Resolution: ~400 m (nadir)
- Swath: 3,029 km
- Repeat Time: 1 day
- Design Life: 7 years

PROPOSED

LINK: http://www.ipo.noaa.gov/Technology/viirs_summary.html

C.5. Terra & Aqua

Terra & Aqua

TERRA
The EOS Flagship

Aqua

Aqua is designed to acquire precise atmospheric and oceanic measurements to provide a greater understanding of their role in the Earth's climate and its variations. Terra provides global data on the state of the atmosphere, land, and oceans, as well as their interactions with solar radiation and with one another. The satellites' instruments provide regional to global land cover, land cover change, and atmospheric constituents. Japan, Canada, and the U.S. have provided instruments for this mission. MODIS operates aboard both Terra and Aqua.

MEASUREMENTS:

- High-resolution images and maps of land surface temperature (Terra)
- Earth's radiation budget and atmospheric radiation (Both)
- Atmospheric temperature (Aqua)
- Cloud properties and water vapor profile (Aqua)
- Vegetation dynamics and soil moisture (Aqua)
- Snow cover and sea ice (Aqua)

PECAD USE:

- Possible use for precipitation and soil moisture

LINKS:

- http://terra.nasa.gov
- http://aqua.nasa.gov

VITAL FACTS:

- Orbit Type: Sun-Synchronous
- Altitude: 705 km (Aqua) and 720 km (Terra)
- Inclination: 98.2°
- Cross-time: 10:30 am (Terra), 1:30 pm (Aqua)
- Launch Date: May 4, 2002 (Aqua), and December 18, 1999 (Terra)
- Design Life: 6 years (Aqua), and 5 years (Terra)

OWNER:

- U.S., NASA
- U.S., JPL

C.6. Landsat 7

Landsat 7

NASA's Landsat provides well-calibrated, multispectral, moderate resolution, substantially cloud-free, sunlit digital images of the Earth's continental and coastal areas with global coverage on a seasonal basis using the Enhanced Thematic Mapper Plus instrument. Operations were transferred to the U.S. Geological Survey in 2000.

MISSION SENSORS:

- ETM+ (Enhanced Thematic Mapper Plus)

VITAL FACTS:

- Orbit Type: Sun-Synchronous
- Altitude: 705 km
- Inclination: 98.2°
- Launch Date: April 15, 1999
- Design Life: 5 years

OWNERS:

- U.S., NASA
- U.S., USGS

MEASUREMENTS:

- Land cover and land use change
- Vegetation dynamics

LINKS:

- http://landsat7.usgs.gov/
- http://landsat.gsfc.nasa.gov/

C.7. Landsat-5

Landsat 5

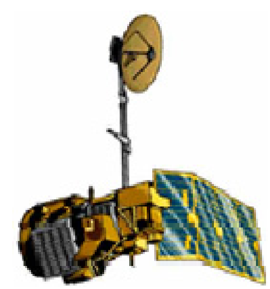
The fifth in a series of Earth observation platforms, Landsat 5 continued the Thematic Mapper archive started in 1982. Current transmissions are by direct downlink only, as there is no recording capability.

MISSION SENSORS:
- MSS (Multispectral Scanner)
- TM (Thematic Mapper)

VITAL FACTS:
- Orbit Type: Sun-synchronous
- Altitude: 705 km
- Launch Date: March 1, 1984
- Design Life: 5 years (exceeded)

OWNERS:
- U.S., NASA
- U.S., USGS

MEASUREMENTS:
- ground cover and land use imagery



LINK:
- http://geo.arc.nasa.gov/sge/landsat/landsat.html

C.8. TRMM

TRMM
(Tropical Rainfall Measuring Mission)

TRMM is a joint mission between NASA and the National Space Development Agency (NASDA) of Japan to monitor and study tropical rainfall and the associated release of energy that helps to power the global atmospheric circulation shaping both weather and climate around the globe.

MISSION SENSORS:

- CERES (Clouds and the Earth's Radiant Energy System)
- LIS (Lightning Imaging Sensor)
- PR (Precipitation Radar)
- TMI (TRMM Microwave Imager)
- VIRS (Visible and Infrared Scanner)

VITAL FACTS:

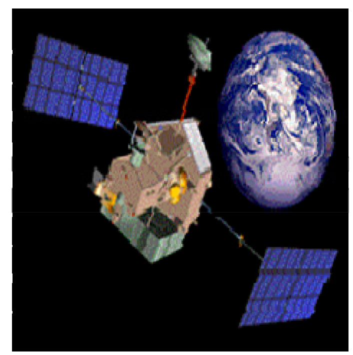
- Orbit Type: Non Sun-Synchronous
- Altitude: 350 km
- Inclination: 35°
- Launch Date: November 27, 1997
- Design Life: 3 years (exceeded)

MEASUREMENTS:

- Earth's radiation budget and atmospheric radiation
- 3-D rainfall distribution over land and oceans
- Cloud radiation, cloud distribution and height, and rain estimates from brightness temperature
- Lightning distribution and variability over the Earth

OWNERS:

- U.S., NASA
- Japan, NASDA



LINK:

- http://trmm.gsfc.nasa.gov

C.9. QuikSCAT

QuikSCAT
(Quick Scatterometer)

QuikSCAT, a "quick recovery" mission to fill the gap created by the loss of data from NSCAT, is benchmarked with the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS) Office of Research and Applications. QuikSCAT is currently intended to record sea-surface wind speed and direction data for global climate research and operational weather forecasting and storm warning.

MISSION SENSOR:
- SeaWinds

VITAL FACTS:
- Orbit Type: Sun-Synchronous
- Altitude: 803 km
- Inclination: 98.6°
- Launch Date: June 19, 1999
- Design Life: 2 years

MEASUREMENTS:
- Sea surface wind velocity and wind direction
- Sea ice distribution

OWNER:
- U.S., NASA

LINK:
- http://winds.jpl.nasa.gov/missions/quikscat/quikindex.html

Appendix D. Relevant NASA Earth Science Products

D.1. MOD 28: Sea Surface Temperature

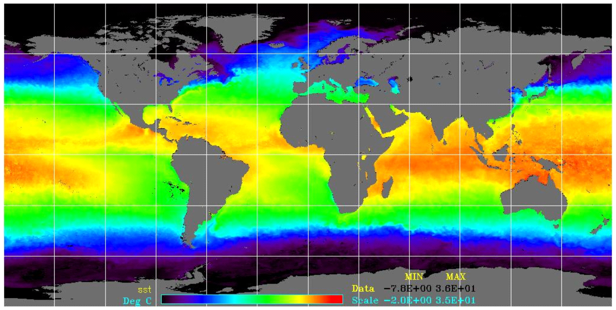
MOD 28: Sea Surface Temperature

MOD 28 provides sea surface temperature over the global oceans during either day or night.

- Accuracy: ±0.2 ˚C for 2˚ x 2˚ squares; 0.3–0.5 K
- Intrinsic Spatial Resolution: TBD
- Applications: Obtaining sea-surface temperature to study energy and hydrological balance, climate-change models
- Parameter: Sea surface temperature
- Web Link:

  http://modis.gsfc.nasa.gov/data/dataproducts.php?MOD_NUMBER=28

- Principal Investigator: Otis Brown
- Science Quality Status: Provisional as of November 1, 2000
- Distribution: GSFC Earth Sciences Data Active Archive Center (GES DAAC)



Sea Surface Temperature

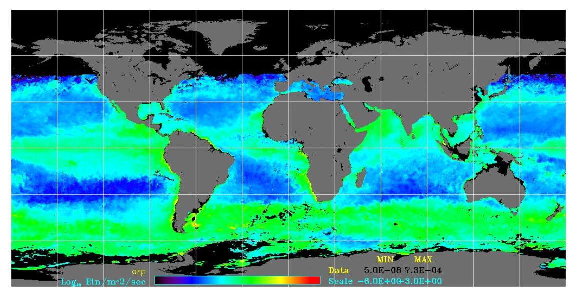
D.2. MOD 22: Photosynthetically Available Radiation

MOD 22: Photosynthetically Available Radiation

MOD 22 consists of four related parameters that describe the irradiance at the ocean surface. The four parameters measure Downwelling Solar Irradiance, Instantaneous Photosynthetically Active Radiation (IPAR), PAR, and Absorbed Radiation by Phytoplankton (ARP).

- Accuracy: 5–10%
- Intrinsic Spatial Resolution: TBD
- Applications: Measures incident irradiance just above the sea surface, total downwelling flux of photons just below the surface, and the irradiance averaged over an entire day
- Parameters:
  - Downwelling Solar Irradiance
  - Instantaneous Photosynthetically Active Radiation (IPAR)
  - Photosynthetically Active Radiation (PAR)
  - Absorbed Radiation by Phytoplankton (ARP)
- Web Link:

  http://modis.gsfc.nasa.gov/data/dataproducts.php?MOD_NUMBER=22
- Principal Investigators: Mark Abbott and Kendall Carder
- Science Quality Status: Provisional as of November 1, 2000
- Distribution: GSFC Earth Sciences Data Active Archive Center (GES DAAC)



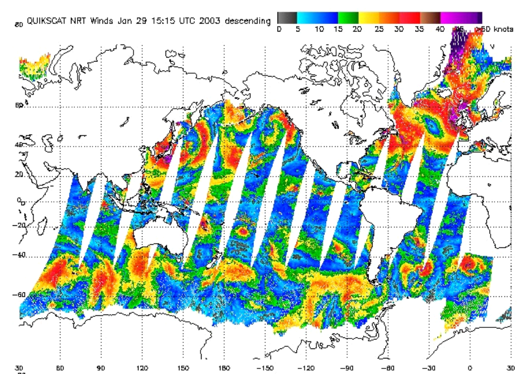
Absorbed Radiation by Phytoplankton

D.3. SeaWinds: Wind Speed and Direction

SeaWinds: Wind Speed and Direction

The SeaWinds instrument provides scientists with information on wind direction and wind speed over the world's oceans. The data can be used to identify changes in the global climate and gain a better understanding of global weather abnormalities. The latest SeaWinds instrument, onboard Japan's ADEOS II, is capable of mapping the wind speed and direction across 90% of the Earth's ice-free oceans every two days.

- Accuracy: Speed: $\pm$2 m/s, Direction: $\pm 20^{o}$ with wind-direction measurement resolution of 25 km
- Intrinsic Spatial Resolution: 25 km
- Applications: Improvements in global weather forecasting and new insights into various Earth research investigations
- Parameters:
  - Wind speed over Earth's oceans
  - Wind direction over Earth's oceans
- Web Link: http://winds.jpl.nasa.gov
- Principal Investigator: Dr. Michael Freilich
- Science Quality Status: TBD
- Distribution: Physical Oceanography Distributed Active Archive (PODAAC)



D.4. MOD 24: Organic Matter Concentration

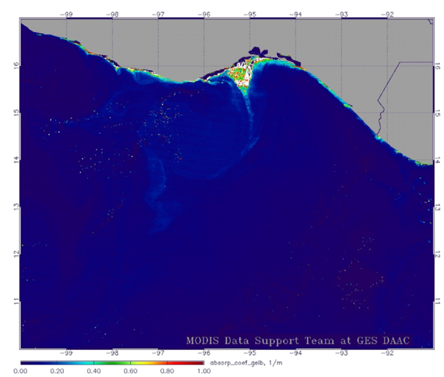
MOD 24: Organic Matter Concentration

This set of products (MOD 19, 23, 24, 26) provides particle concentrations in Case 1 sea water, which have optical properties dominated by chlorophyll and associated covarying detrital pigments.

- Accuracy: TBD
- Intrinsic Spatial Resolution: TBD
- Applications: Ocean productivity, biogeochemical models, which can ultimately be used for global climate models
- Parameters:
  - Particulate organic matter concentration
  - Dissolved organic matter concentration
- Web Link:

  http://modis.gsfc.nasa.gov/data/dataproducts.php?MOD_NUMBER=24

- Principal Investigator: Dennis Clark
- Science Quality Status: Provisional as of November 1, 2000
- Distribution: GSFC Earth Sciences Data Active Archive Center (GES DAAC)



Gelbstoff absorption coefficient at 400 nm

D.5. MOD 21: Chlorophyll_a Pigment Concentration

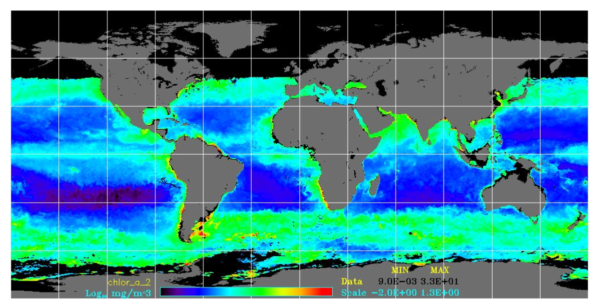
MOD 21: Chlorophyll_a Pigment Concentration

MOD 21 contains ocean chlorophyll_a pigment concentration for Case 1 and Case 2 waters. Valid data exist only for ocean cloud-free pixels.

- Accuracy: 35%, 0.01 to 50 mg/m^2
- Intrinsic Spatial Resolution: TBD
- Applications: Absorption parameters generated by the chlorophyll algorithm are also provided as the intermediate product MOD 36
- Parameter: Ocean chlorophyll_a pigment concentration
- Web Link:

  http://modis.gsfc.nasa.gov/data/dataproducts.php?MOD_NUMBER=21

- Principal Investigator: Kendall Carder
- Science Quality Status: Provisional as of November 1, 2000
- Distribution: GSFC Earth Sciences Data Active Archive Center (GES DAAC)



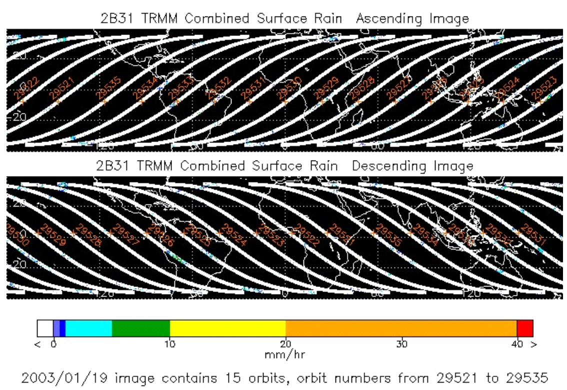
Chlorophyll_a Concentration

D.6. TRMM 2B-31: Rainfall Combined

TRMM 2B-31: Rainfall Combined

2B31 provides the vertical structure of rainfall (rates and drop-size-distribution parameters) based upon the TRMM microwave imager (TMI) and the TRMM radar (PR), within the PR swath. Combined PR/TMI rain rate and path-integrated attenuation at 4 km horizontal, and 250 m vertical, resolutions, over a 220 km swath.

- Accuracy: TBD
- Intrinsic Spatial Resolution: TBD
- Applications: rainfall estimates, brightness temperatures
- Parameter:
  - TRMM combined rain profile
- Web Link: http://trmm.gsfc.nasa.gov/2b31.html
- Principal Investigator: Jim Weinman
- Science Quality Status: TBD
- Distribution: GSFC Earth Sciences Data Active Archive Center (GES DAAC)

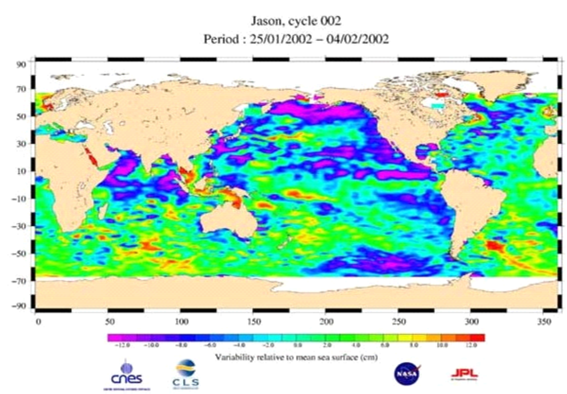


D.7. Jason: Sea Surface Height

Jason: Sea Surface Height

The Jason-1 sea surface height (SSH) product is computed from altimeter range and satellite altitude above the reference ellipsoid. The "reference ellipsoid" is the definition of the non-spherical shape of the Earth as an ellipsoid of revolution. Sea surface height is often shown as a sea-surface anomaly or deviation; this is the difference between the SSH at the time of measurement and the average SSH for that region and time of year.

- Accuracy: 2.5 – 4.2 centimeters
- Intrinsic Spatial Resolution: 1˚
- Applications: Visualization of ocean currents, seasons, research, input to numerical ocean models, education
- Parameter:
  - Distance of sea surface above the reference ellipsoid
- Web Link: http://topex-www.jpl.nasa.gov/index.html
- Principal Investigators: Dr. Lee-Lueng Fu and Y. Menard
- Science Quality Status: TBD
- Distribution: Physical Oceanography Distributed Active Archive (PO.DAAC)



D.8. MOD 02: Level 1B Calibrated Radiances

MOD 02: Level 1B Calibrated Radiances

The Level 1B dataset contains calibrated and geolocated at-aperture radiances for 36 bands generated from MODIS Level 1A scans of raw radiance (MOD 01).

- Accuracy: 5% (1σ)
- Intrinsic Spatial Resolution: 250 m, 500 m, 1 km
- Relationship to Higher Level Products: The Level 1B product provides the radiometrically corrected images derived from the Level 1A data. These are the baseline datasets from which all follow-on MODIS products are generated.
- Web Link:

  http://modarch.gsfc.nasa.gov

- Principal Investigator: V. Salomonson
- Science Quality Status: TBD
- Distribution: GSFC Earth Sciences Data Active Archive Center (GES DAAC)

Terra L1B MODIS image of Cape York, Australia

D.9. AST_L1B L1B Registered Radiance at the Sensor

AST_L1B L1B Registered Radiance at the Sensor

The ASTER L1B product contains radiometrically calibrated and geometrically co-registered data for all the channels acquired previously through the telemetry streams of the 3 different telescopes in Level-1A. Its created by applying the radiometric calibration and geometric correction coefficients to the Level-1A data.

- Accuracy: N/A
- Intrinsic Spatial Resolution: 15 (VNIR), 30 (SWIR), 90 m (TIR)
- Application: Initial data for most ASTER products
- Parameter:
  - Initial radiance data
- Web Link: http://edcdaac.usgs.gov/aster/ast_l1b.html
- Principal Investigator: TBD
- Science Quality Status: Validated May 2, 2001
- Distribution: Land Processes Distributed Active Archive Center (LP DAAC)

D.10. ESMF NSIPP Coupled Ocean-Atmosphere GCM

ESMF EARTH SYSTEM MODELING FRAMEWORK

NSIPP coupled ocean-atmosphere GCM

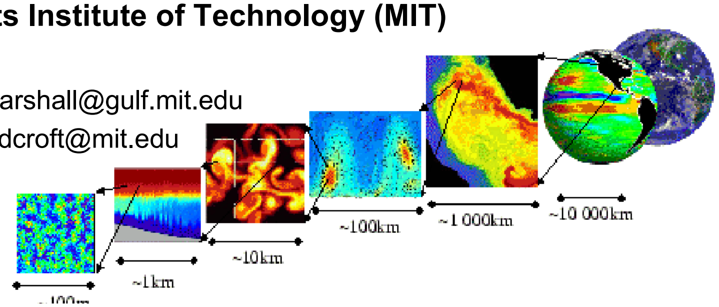
NSIPP finite-difference atmospheric general circulation model (AGCM) coupled to Poseidon ocean general circulation model (OGCM).

- **Physics**
  - For the baseline case, the global AGCM will have 2-degree zonal resolution, 2.5-degree meridional resolution and 34 levels. The global OGCM will gave 1.25^{o} zonal resolution, 2/3^{o} meridional resolution and 20 layers. The AGCM has an empirical cloud diagnostic model and an Arakawa-Schubert boundary-layer parameterization. The OGCM has an explicit Kraus-Turner mixed-layer and implicit vertical diffusion and mixing. Standalone versions of the two codes will be forced by sea surface temperature, and (for the ocean) observed SSMI wind analyses. The two models will also employ ESMF for coupled model integrations.
- **Algorithms**
  - Both models use a structured, generalized orthogonal grid. The baseline cases will employ regular latitude-longitude grids. The AGCM uses fourth-order entrophy-conserving finite differencing with Shapiro and Asselin filters.
- **Computational Profile**
  - Language: F90. Framework: GEMS. Platform: CRAY T3E.
- **Performance**
  - Operational configuration runs on 128 CRAY-T3E PEs.
- **I/O Format and Requirements**
  - Serial I/O by root PE. Unformatted F77 files. Sequential and direct access.

D.11. MITgcm

MITgcm

- The MITgcm (*MIT General Circulation Model*) is a numerical model with the following characteristics:
  - it can be used to study both the **ocean** and **atmosphere**: one hydrodynamic kernel is used to drive forward both atmospheric and oceanic models
  - it has a non-hydrostatic capability and so can be used to study both **small-scale** and **large-scale** processes
  - finite volume techniques are employed yielding an intuitive discretization and support for the treatment of **irregular geometries** using orthogonal curvilinear grids and shaved cells
  - tangent linear and adjoint counterparts are automatically maintained along with the forward model, permitting sensitivity and optimization studies
  - the model is developed to perform efficiently on a wide **variety of computational platforms**
- Host Organization: **Massachusetts Institute of Technology (MIT)**
- POC: support@mitgcm.org
  - John Marshall, (617) 253-9615, marshall@gulf.mit.edu
  - Alistair Adcroft, (617) 253-5938, adcroft@mit.edu
- Websites:
  - http://mitgcm.lcs.mit.edu/
  - http://mitgcm.org/



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14. ABSTRACT
The Coral Reef Early Warning System (CREWS) is operated by NOAA's Office of Oceanic and Atmospheric Research as part of its Coral Reef Watch program in response to the deteriorating global state of coral reef and related benthic ecosystems. In addition to sea surface temperatures (SSTs), the two most important parameters used by the CREWS network in generating coral reef bleaching alerts are 1) wind speed and direction and 2) photosynthetically available radiation (PAR). NASA remote sensing products that can enhance CREWS in these areas include SST and PAR products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and wind data from the Quick Scatterometer (QuikSCAT). CREWS researchers are also interested in chlorophyll, chromophoric dissolved organic matter (CDOM), and salinity. Chlorophyll and CDOM are directly available as NASA products, while rainfall (an available NASA product) can be used as a proxy for salinity. Other potential NASA inputs include surface reflectance products from MODIS, the Advanced Spaceborne Thermal Emission and Reflection Radiometer, and Landsat. This report also identifies NASA-supported ocean circulation models and products from future satellite missions that might enchance the CREWS DST.

15. SUBJECT TERMS
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