Remote Sensing of Aquatic Coastal Ecosystem Processes
Remote Sensing and Digital Image Processing

VOLUME 9

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PREFACE

This book was produced at the invitation of our Publishing Editor at Springer, Petra van Steenbergen. We thank her for the invitation. It is one of a series of remote sensing books (Remote Sensing and Digital Image Processing), each of which addresses a specific topic within the remote sensing field.

Our contribution, unlike the other books in this series, is not aimed at remote sensing scientists. As such, there is very little optical theory in the book with the exception of one chapter which presents in detail the optical algorithms that form the basis of an interactive program (WASI, the “Water colour Simulator”). The program is offered on the CD that accompanies this book, and is in association with a chapter by Peter Gege and Andreas Albert. In this case, technical details are provided for remote sensing scientists who are interested in the optical and theoretical bases for the program. Remote sensing and non-remote sensing scientists alike can manipulate this program to view the effects of various substances (pigments, sediment) on spectra. We thank these authors for this valuable contribution.

Our main target audience consists of aquatic scientists, and managers of coastal aquatic ecosystems. We are both involved in remote sensing at both the science and image processing levels – Laurie is an aquatic biologist, and became versed in remote sensing image processing techniques while employed at NASA’s Ames Research Center, and Ells is a remote sensing scientist who actively carries out science-based field research in support of aquatic remote sensing. Additionally, Ells has been very involved in transferring remote sensing technology to managers in developing nations. Thus we offer a perspective which we hope can be shared by scientists and managers.

The book is divided into three sections: Science Applications, Monitoring Applications, and Management Applications. Each chapter of these sections was written with the appropriate target audience in mind. Thus managers are encouraged to review the final chapters and, if interested, can then delve into the more technical earlier chapters. The book was also written as a resource manual for those who would like a concise overview of specific sensors and their applicability for specific aspects of coastal ecosystems. Again, discussions of optics and sensor development theory are kept at a minimum.

We would like to thank our authors, who graciously accepted fitting into our specific concept for this book. We especially would like to thank Candace Newman, who produced the final figures for the book and Alan Lim who took on the laborious task of the index.

Each chapter in this book was reviewed by one or both of us, as well as anonymously by at least one of the chapter first authors.

Laurie L. Richardson
Ellsworth F. LeDrew
Chapter 1

REMOTE SENSING AND THE SCIENCE, MONITORING, AND MANAGEMENT OF AQUATIC COASTAL ECOSYSTEMS

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1. Introduction

Many books and scientific journals address the use of remote sensing in the context of its applicability to aquatic ecosystems. The most successful and widespread aquatic remote sensing connection to date has been remote sensing of the open oceans. This effort has been supported by many in-depth studies of the optics of “blue” or Case 1 waters. Tremendous strides in this field have led to global data bases in support of scientific models now used to study our Earth as a whole, and have led to integration of quantitative world-wide data sets into studies of such hemispheric and global scale problems as climate change. This success has been matched by the design and deployment of an ongoing series of space-borne remote sensors specific to the oceans. It has also led to the existence of global data sets and data products that are easily accessed and interpreted by managers.

A much less studied, but at least equally important, aquatic ecosystem that could benefit greatly from remote sensing technologies is the aquatic coastal zone. Such zones are of importance in terms of ecology and human populations. They are valuable in terms of biodiversity, as resources, and for their role in connectivity between terrestrial and aquatic habitats. Over 50% of human populations live in coastal zones.

The coastal zone has long been a target for science-based study, often in the context of the biology and ecology of this complex and interacting system. Algal and fish biologists, in particular, have intensively studied this zone. Scientific disciplines specific to coastal zones include study of estuaries, coral reefs, and the coastal zone as a nursery. Such studies are often interdisciplinary, relying on techniques in biology, chemistry, physical processes, and more recently molecular markers. Many of these studies involve coastal ecosystem dynamics and change.

Perturbations and long-term changes in coastal stability have ramifications at many levels, including impacts on fisheries, flooding of human populations and infrastructure, eutrophication, development of toxic algal blooms, etc. It is within the realm of aquatic ecosystem managers to be aware of and prepared to counteract or mitigate such perturbations. This task is daunting, largely as a result of the regional scale and dynamic nature of aquatic coastal zones. It also often demands interactions with aquatic scientists.

One of the most useful tools for both scientists and managers for the study of coastal zones is remote sensing. The benefits or remote sensing include synoptic, quantitative data sets that are regional (as well as local and global) in scale, and that can offer repeat sampling. In many cases archival remote sensing data are available that are invaluable in providing a history of the region. The disadvantages of remote sensing...
commonly include cost, lack of remote sensors tailored for coastal zones, and, perhaps most important, an underdeveloped line of communication between scientists, remote sensing experts, and managers. Despite these drawbacks, there are many current and ongoing examples of the successful use of remote sensing to support aquatic coastal ecosystem science, and to integrate remote sensing into the management of coastal zones. We hope to provide an overview of the integration of remote sensing and both science and management in this book.

2. Coastal zones

The apparent lag in coastal aquatic remote sensing as compared to open ocean remote sensing is, we believe, in large part due to the complexity of the coastal zone. This complexity is multifaceted, and includes both optical and biological complexity as well as an overlay of temporal and spatial dynamics. In terms of optical complexity, many factors are involved. These include the following:

- coastal zones are often shallow, thus bottom reflectance contributes to an optical water-leaving signal
- benthic communities of differing complexities and depths also contribute to optical water-leaving signals
- phytoplankton and suspended sediments are present in much higher concentrations in coastal zones as compared to “blue” offshore water
- spectral signatures of different types of phytoplankton and sediments are highly variable and can strongly affect spectral reflectance
- spectral signatures of phytoplankton and sediments interact in such a manner that specific algorithms must be derived that are tailored for coastal regions.

In terms of biological complexity, the following factors must be addressed:

- the presence of macroalgae, dense invertebrate communities (such as found on coral reefs) and other bio-optically active organisms can contribute to reflectance
- the effect of biota, both benthic and suspended, on traditional (Case 1) chlorophyll algorithms often results in erroneous results
- seasonal patterns of biomass and dominance by successive members of the biological community commonly occur.

Finally, temporal and spatial dynamics are much more relevant for remote sensing of aquatic coastal zones than for those of open oceans. Thus, transient phytoplankton blooms, runoff from storms, flooding, and resuspension of sediments due to storm events all must be considered within spatial scales that may not be resolved by existing satellite sensors.

3. Spectral signatures

We believe that one of the most promising features of coastal aquatic systems that can be exploited for both science and management applications of remote sensing is that of spectral signatures. Case 2 (coastal) waters, as opposed to Case 1 (oceanic)
waters, are dominated by in-water features as opposed to scattering. This is particularly true of phytoplankton at the concentrations found in the coastal zone, which are typically orders of magnitude higher than those of Case 1 waters. An important ramification of this fact is that the widely used chlorophyll algorithms for ocean chlorophyll break down under high concentrations of phytoplankton and/or suspended sediment such as are typically found along the coast. Depending on the concentrations, types, and proportions of phytoplankton and suspended sediments, Case 1 chlorophyll algorithms can lead to either under- or over-estimation of chlorophyll concentration. This is the basis for the ongoing and costly reanalysis of Coastal Zone Color Scanner (CZCS) data, which were originally analyzed using algorithms designed for blue offshore waters. The spectral bands on the CZCS, in fact, were selected based on Case 1 chlorophyll algorithms.

The optical properties of Case 2 waters are very different from those of Case 1 waters. Spectral analysis of Case 2 waters can provide relatively much more information about the type(s) of both phytoplankton and sediment present in the water column, information which is useful to scientists and managers alike. This is possible due to the strong effects that these water constituents have on the water-leaving optical signals of coastal waters when they are present at high concentrations such as found near the coast. This subject is addressed in detail in Chapter 3 by John Schalles. In this chapter experimental manipulations of phytoplankton (type and concentration), sediments of different types, and combinations of phytoplankton and sediment were analyzed in terms of spectral reflectance and existing chlorophyll algorithms. This concept is further developed and illustrated in Chapter 4 by Peter Gege and Andreas Albert. These authors have also provided an interactive software program in which users can manipulate sediment and pigment constituents in a water column and observe the effects on spectra. Chapter 4 includes the optical theory and algorithms that support the interactive program.

In addition to phytoplankton and sediment signatures, many benthic communities exhibit distinctive spectral signatures detectable using remote sensing. One of the most successful coastal applications taking advantage of this is that of remote sensing of coral reefs, which is addressed in several chapters in this book (e.g. Chapter 11 by Newman et al.). Thus although the coastal zone is optically complex, this complexity in itself can be the basis for extending the potential of remote sensing beyond what is possible for Case 1 waters.

4. Science based connections between ecosystem processes and remote sensing

Many features of aquatic coastal ecosystems have strong optical signals. These include the various photoreactive, photoprotective, and light harvesting pigments of phytoplankton, submerged and emergent macroalgae, and coastal (terrestrial) plants. Many of these organisms also have unique pigment combinations as well as indicator fluorescence signals. Thus such populations can be monitored, measured, and identified using optical properties.

Use of optical features in coastal biology is widespread and implemented by both scientists and managers alike. The most common is optical (spectrophotometric) detection of chlorophyll to estimate phytoplankton concentration and thus monitor potential eutrophication as a proxy for the “health” of the aquatic ecosystem. This approach is now being expanded to detect pigment signatures specific to toxin
producing algae. In each case, the fundamental basis for the signals (i.e. the pigments themselves) can be detected using remote sensing.

Most of the Case 1 studies on remote sensing of pigments (primarily chlorophyll $a$) have focused on optics and algorithm development. The parameter that is deemed most important is radiative transfer, which is a composite of backscattering, absorption, transmission, fluorescence, etc. As a result, much of this work results in publications that are dominated by optical modeling and radiative transfer equations. This approach is necessary because most water-leaving reflectance spectra in Case 1 waters are quite similar.

In contrast, the water-leaving reflectance of Case 2 waters is often highly variable and can be detected with the eye alone. Thus, in a different approach, there is a body of work on Case 2 algal pigment remote sensing that foregoes preliminary radiative transfer modeling and instead focuses directly on spectral signatures. Differences in the spectra themselves then become the basis for algorithm development.

Coastal phytoplankton are often dynamic in terms of phytoplankton population composition and quantity of cells, both of which can dramatically affect spectral reflectance. Thus detection of specific spectral patterns, or signatures, can often detect a specific type of algal bloom. The connection between pigments and algal type is one of the most promising and applicable examples of the potential for bridging coastal ecosystem processes and remote sensing.

As mentioned above, one of the benefits of remote sensing for studies of aquatic coastal zones is the ability of remote sensing to provide synoptic data sets at different scales. This is accomplished by the availability of sensors with different spatial resolutions. An enhancement of this capability is the fact that many sensors offer different spectral, as well as spatial, resolution. The result is that synoptic remote sensed data can be attained for a given coastal zone that can detect and assess many different aspects of that particular coastal aquatic ecosystem. Therefore, in addition to discriminating between phytoplankton types, remote sensing can allow for habitat mapping, coastal shoreline anomalies, and change detection.

Remote sensing can also detect certain physical properties that are directly or indirectly crucial to aquatic ecosystem processes. One of the most important of these is water surface temperature. Temperature is an important factor in the physiological functioning and health of organisms. It is also a major factor in controlling population dynamics of many aquatic organisms. The combination of optical signals that can detect, identify, and quantify different types of aquatic organisms, along with the capability to detect an important and regulatory factor such as temperature, leads to the potential for remote sensing as a powerful tool to study and quantify aquatic ecosystems at the physiologically functional level.

Current research is aimed at using remote sensing to directly scale up aquatic ecosystem studies at the process level. An example of such an effort is presented by John Brock and colleagues in Chapter 5. This research group is using a suite of remote sensors with different spatial and spectral resolution as well as different remotely sensed factors to measure and extrapolate carbon biogeochemical processes on a coral reef to the regional scale. Their program includes remotely sensed mapping of the reef itself (geomorphology), remote sensing based detection of different habitats/groups of organisms (biotopes), and scaling up of in situ experimental measurements, based on the remote sensing data, to examine reef “metabolism”. While this chapter is particularly innovative and beyond the scope of most monitoring and managing programs, it is included as an example of a feasible and existing remote sensing application. Another example of this type is found in Chapter 6 by Jim Hendee et al.,
who are moving towards remote sensing of coral health by remote measurement of coral photosynthetic efficiency.

5. Monitoring coastal zones, habitats, and ecosystems

Although many aquatic monitoring programs incorporate remote sensing, often the degree of incorporation is prohibited by cost and a well-founded perception that remote sensing requires expertise in a highly specialized field. Despite this, the success of remote sensing in monitoring can only suggest that this approach will become increasingly common in the future. Buoys with monitoring sensors are increasing in number, as are their data capabilities. Such buoys are now used to, for example, measure and estimate chlorophyll and turbidity in the water column - an assessment of water quality. Some innovative programs, particularly in Australia and Europe, include fully integrated optical remote sensing (satellite and aircraft) data input for the early detection of harmful algal blooms. A specific case study is presented in Chapter 10 in which Stuart Phinn et al. discuss the use of remote sensing monitoring to detect toxic blooms of the cyanobacterium *Lyngbya majuscula*. In this particular case, the use of remote sensing in monitoring is also integrated into management.

Satellite platforms that support remote sensing now provide global coverage. Currently remote sensing capabilities and data streams exist that could be used much more extensively in monitoring programs. Additionally, historical data are available which can potentially be a source of baseline data, an increasingly important concept in monitoring aquatic coastal environments. An overview, discussion of data sets, and example of use of historical data are given in Chapter 8 by Jennifer Gebelein.

One global ecosystem that is currently the focus of study on a world-wide basis, and that makes extensive use of satellite data for mapping and monitoring, is the coral reef ecosystem. Many of the chapters in this book include some aspect of remote sensing of coral reefs. These include mapping on a global basis, which is being conducted as the first step of global monitoring of coral reefs; remote sensing based studies of coral reef health; use of remote sensing to scale up coral reef process level studies; and integration of historical data in coral reef/land interaction studies. Rather than compile these efforts into one section on remote sensing of coral reefs, we have placed individual studies within the framework of remote sensing and science, monitoring, and management as a recurrent thread throughout the book.

It is our hope that this book will alleviate some of the hesitation of those involved in monitoring of aquatic coastal zones and ecosystems by providing a non-technical overview of this field as well as a compilation of remote sensing resources.

6. Management of coastal zones, habitats, and ecosystems

Even more so than within monitoring programs, remote sensing is an underutilized tool that would greatly benefit management programs that are responsible for, or include, coastal ecosystems. However, managers are often more reluctant than those involved in monitoring to introduce remote sensing. This is, again, based on the view that expertise if required, and is enhanced by the fact that many managers, as opposed to monitoring personnel, do not have a science background. In cases where underdeveloped nations are involved, the problem is pronounced.

We have included in this book particular attention to bridging the gap between managers and remote sensing. Chapter 9 by Brian Whitehouse and Daniel Hutt
presents an overview, aimed at managers, that discusses the benefits and potential of remote sensing for management of coastal aquatic ecosystems, as well as a discussion of cost and financial issues. Chapter 11 by Candace Newman et al. extends this discussion to specifically address technology transfer of remote sensing to underdeveloped countries, including local communities. These concepts are further extended to policy making in Chapter 10 by Stuart Phinn and colleagues.

One of the most important and encompassing roles of managers is integration of data within and between the diverse areas of social, natural resource, economic, and environmental frameworks. Incorporation of remote sensing at the management level also includes data integration, but with a different aim – that of not only extracting and integrating data from various sensors, but transferring this knowledge to the wider community. Such topics are addressed, and examples of successful efforts are provided, in Chapter 12 by Julie Robinson et al.

7. Integrating remote sensing, science, monitoring, and management

The integration of science and remote sensing is now a reality. One of the best examples of success is the use of remote sensing to predict coral bleaching, as presented by William Skirving and colleagues in Chapter 2. The science-based data that have proven the connection between physiological thermal stress and coral bleaching are now fully integrated into automated remote sensing data analyses that allow real-time world-wide coral bleaching “alerts”. The accuracy of these alerts in predicting bleaching is extremely high. Thus in this case scientists have provided a quantitative link between an aquatic ecosystem process and a factor (sea surface temperature) detectable at global scales using remote sensing. Managers now routinely access real-time satellite-derived predictive data that is directly relevant to the health of the ecosystem they are managing – coral reefs.

This approach has been extended using another type of remote sensing instrument package – permanently moored buoys that support an array of different sensors that measure factors of importance to aquatic scientists, in particular biologists, and managers. A state of the art system is described here in Chapter 6 by Jim Hendee and colleagues. In addition to an overview of the system and examples of how these data can support science applications, a guideline for design and deployment of the system is provided for managers.

Another example is the use of remote sensing in support of management of coastal flooding. In Chapter 7, Tim Webster and Donald Forbes present a detailed case study in which remote sensing is being used to mitigate the effects of coastal flooding based on the results of light detection and ranging (LIDAR). Thus in this case, as opposed to those discussed above, purely physical features (details of varying coastal elevations) are integrated with historical data bases to predict flooding effects. City managers are actively integrating these remote sensing data with planning.

8. Summary

All of the chapters in this book are meant to serve as resources for both scientists and managers. In addition to the specific examples of remote sensing in science, monitoring, and management briefly summarized above, the chapters by lead authors Jennifer Gebelein, Brian Whitehouse, Stuart Phinn, Candace Newman, and Julie Robinson include overviews of data bases, comparisons of sensor capabilities, and the
existence of archived data sets. These are provided in potential support of scientists and managers who would like to integrate remote sensing into individual projects. We hope that this resource will further inspire incorporation of remote sensing into the study and management of aquatic coastal and shallow-water ecosystems and processes.
Section I

Science Applications
Chapter 2

EXTREME EVENTS AND PERTURBATIONS OF COASTAL ECOSYSTEMS
Sea Surface Temperature Change and Coral Bleaching

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1. Introduction

Remote Sensing of Aquatic Coastal Ecosystem Processes presents many examples of remote sensing tools which could be used in an operational sense for the benefit of management of various aspects of coastal ecosystems. This chapter will present the World’s first global operational satellite products designed specifically to help coral reef managers map and monitor anomalous sea surface temperatures (SST) and hence better understand and predict mass coral bleaching. These products are possibly the only global suite of operational satellite products currently being used for the management of any marine ecosystem.

Coral bleaching occurs when there is widespread loss of pigment from coral, mainly due to the expulsion of symbiotic algae (Yonge and Nicholls, 1931). The algae are usually expelled in times of stress, often caused by sea surface temperatures which are higher than the coral colony’s tolerance level. This may be as little as 1 to 2°C above the mean monthly summer values (Berkelmans and Willis, 1999; Reaser et al., 2000).

A number of publications in the early 1990s reported that links had been observed between significant bleaching and anomalously warm water several weeks earlier (e.g. Bermuda: Cook et al. 1990; Indonesia: Brown and Suharsono, 1990; Jamaica: Gates, 1990; Andaman Sea: Brown et al., 1996). About the same time a number of journal articles proposed a mechanism that linked sea surface temperature with mass coral bleaching (e.g. Lesser et al., 1990; Glynn and D’Croz, 1990). Coles and Jokiel (1977) and Jokiel and Coles (1990) proposed the existence of a universal critical threshold temperature for bleaching. They proposed that regardless of location, the threshold could be defined as a 1°C increase over the mean local summer maximum temperature. As an extension of these ideas, Goreau and Hayes (1994) produced maps of “ocean hot spots” using monthly global ocean temperature anomaly maps from NOAA Climate Diagnostic Bulletins (monthly maps derived mostly from in situ data with a small satellite contribution). These “ocean hot spots” identified areas whose SSTs exceeded long term averages by more than 1°C. Bleaching seemed to be occurring within the boundaries of the “ocean hot spots” for the warm season in each region.

One of us (Dr. Alan Strong-NOAA/NESDIS) recognized that there was an opportunity to derive an automated satellite product based on this relationship. As a result, the HotSpot product was born, which served as the basis of the NOAA Coral Reef Watch Program. HotSpot was first presented as an experimental product in 1997 (Strong et al., 1997). This proved to be somewhat fortuitous given that we now know...
that 1998 turned out to be the most significant year for mass coral bleaching in known history.

The HotSpot product gained widespread recognition when, in early 1998, Dr. Strong announced that the Great Barrier Reef (NE Australia) was bleaching before either the Great Barrier Reef Marine Park Authority (GBRMPA) or the Australian Institute of Marine Science (AIMS) knew about it. Out of the realization that this product was potentially a very powerful satellite tool for coral reef management, a formal agreement was signed between NOAA, AIMS and the GBRMPA to work together on the development of new and improved satellite products for monitoring coral reef health. As a result of this agreement, and a series of workshops, the HotSpot product suite has grown and the understanding of the mechanisms and management actions associated with coral bleaching have vastly improved.

This chapter will describe the operational HotSpot product suite and each of its derivations.

2. Sea Surface Temperature Data

NOAA has been producing sea surface temperatures from satellite data since 1972. Monitoring SST from earth-orbiting infrared radiometers has had a wide impact on oceanographic science. Currently, one of the principal sources of infrared data for SST measurement is the Advanced Very High Resolution Radiometer (AVHRR), which has been carried on NOAA’s Polar Orbiting Environmental Satellites (POES) since 1978. It is a broad-band, four or five channel (depending on the model) scanner, with sensors in the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum (http://www.ngdc.noaa.gov/seg/globsys/avhrr.shtml). The POES satellite system offers the advantage of daily global coverage, by making near-polar orbits roughly 14.1 times every 24 hours. In situ SSTs, from buoys (drifting and moored) are used operationally for calibration purposes to maintain accuracy, removing any biases, and compiling statistics with time (McClain, 1985; Strong, 1991; and Strong, et al. 2000).

The composite AVHRR-SST products have a resolution of 50km and are produced twice-weekly in near real-time. On Tuesdays data from the previous three days (Saturday through Monday) are used, and on Saturdays data from the previous four days (Tuesday through Friday). Since the AVHRR is limited to a temporal resolution of six hours (when combining data from both operational satellites), it is not possible to accurately characterize the diurnal variation in SST caused by the cyclic heating of the sea surface as the sun changes its’ angle during the day and its absence during the night. While some of NOAA’s operational SST products use blended day and night retrievals, nighttime-only observations are used in many SST products in an effort to minimize the effects of diurnal variation. Nighttime SST products compare most favorably with in-situ buoy SSTs at 1 meter depths (Montgomery and Strong, 1995). An example of the global nighttime composite AVHRR-SST product can be seen in Figure 1.

The nighttime AVHRR-SST products were primarily developed for NOAA’s Coral Reef Watch (CRW) Program for both monitoring and assessment of coral bleaching. CRW’s other satellite monitoring and assessment products include SST anomalies, coral bleaching HotSpots, Degree Heating Weeks (DHW), Tropical Coral Bleaching Indices, and SST time series, including on-line animations. The development and production of these CRW products takes place within the NOAA National Environmental Satellite, Data, and Information Service (NESDIS). This NESDIS team is comprised of
Figure 1. NOAA 50km Nighttime SST product for 2nd September, 2002.
scientists from the Marine Applications Science Team (MAST) in the Oceanic Research and Applications Division (ORAD) of the Office of Research and Applications (ORA) and from the Product Systems Branch (PSB) of the Information Processing Division (IPS) of the Office of Satellite Data Processing and Distribution (OSDPD).

3. The Coral Reef Watch SST Anomaly Product

CRW’s first product consisted of a simple SST anomaly based on a nighttime AVHRR climatology data set from 1985 to 1993. The climatology was derived by averaging weekly mean nighttime SSTs into monthly means over the nine year period, and then producing the 12 monthly means from all nine years of data. The actual daily SST anomaly was derived after the monthly means had been interpolated into daily means. This product supports wide ranging uses and is the preferred product for the NESDIS’ National Climate Data Center (NCDC) when observing the onset and effects of El Nino and La Nina (http://www.ncdc.noaa.gov/oa/climate/elnino/elnino.html). The SST Anomaly product became officially operational in 2001 (see Figure 2 for an example of the SST Anomaly product).

4. The Coral Reef Watch Bleaching HotSpot Product

Early in 1997, NESDIS began developing global satellite 50-km resolution experimental products (initially SST Bleaching HotSpots, and then DHW products) as indices of thermal stress-related coral bleaching. These products are the outgrowth of earlier work by Montgomery and Strong (1994) and Gleeson and Strong (1995). The HotSpot product became officially operational in 2001 (see Figure 3 for an example of the HotSpot product).

The coral bleaching HotSpot is not a typical climatological SST anomaly. It is a measure of the occurrence of the hottest SST for a region and as such is an anomaly that is not based on the average of all SST, but on the climatological mean temperature of the climatologically hottest month (i.e. the maximum of the monthly mean SST climatology, often referred to as the MMM climatology). Since the HotSpot is an anomaly based on the maximum of the monthly mean SST, negative values are meaningless in this context; therefore only positive values are displayed.

5. The Coral Reef Watch DHW Product

HotSpot values provide a measure of the intensity of sea surface thermal stress, but do not measure the cumulative effects of that thermal stress on a biological system such as a coral reef. In order to monitor this cumulative effect, a thermal stress index, the Degree Heating Week (DHW), was developed. DHW represents the accumulation of HotSpots for a given location over a rolling 12-week time period. Preliminary results indicate that a HotSpot value of less than one degree is insufficient to cause visible stress on corals. Consequently, only HotSpot values ≥1°C are accumulated (i.e. if we have consecutive HotSpot values of 1.0, 2.0, 0.8 and 1.2, the DHW value will be 4.2 because 0.8 is less than one and therefore not used). One DHW is equivalent to one week of HotSpot levels staying at 1°C or one ½ week of HotSpot levels at 2°C, and so forth. For an example of the DHW product, see Figure 4.
Extreme Events and Perturbations
Figure 3. NOAA 5km HotSpot product for 2nd September, 2002.