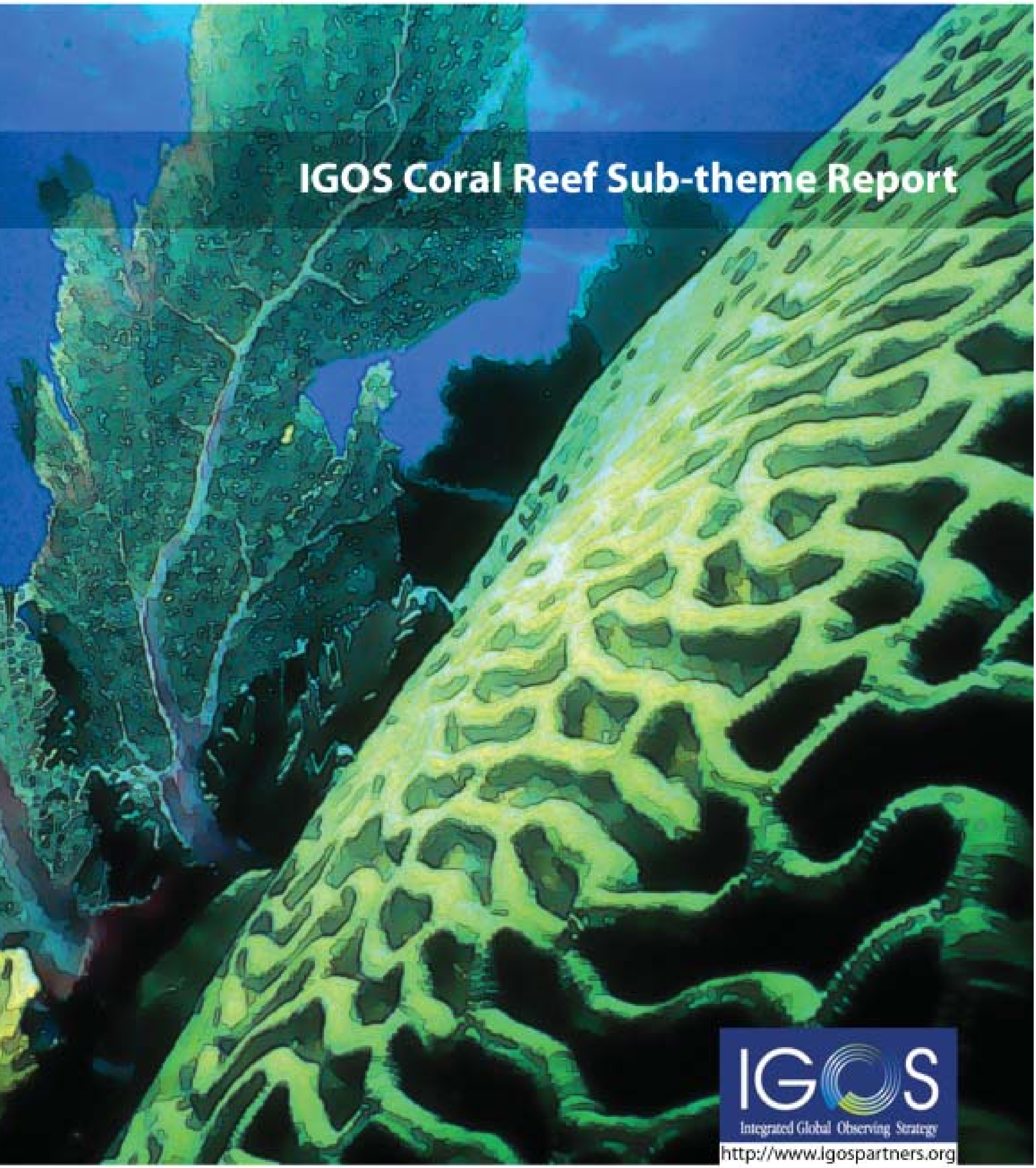
IGOS Coral Reef Sub-theme Report



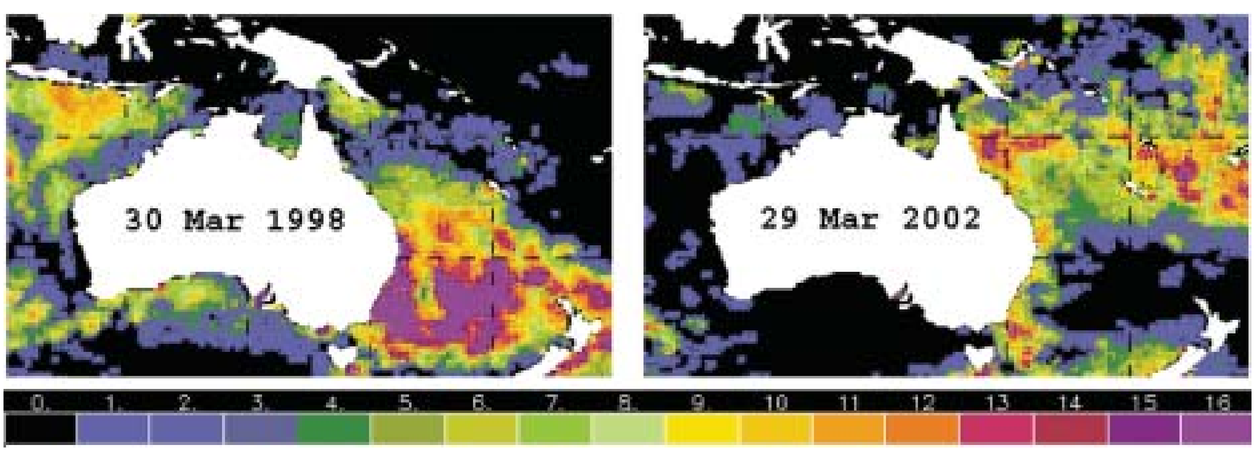
IGOS

Integrated Global Observing Strategy

http://www.igospartners.org

Report: Approved by the IGOS Partners

5 June 2003



DHW Chart for the end of March 1998 (left) and 2002 (right) showing the accumulation of HotSpots over the summer (December through March). Units are in °C-weeks.

Feeding polyps on massive coral head. Dr. James McVey, NOAA Sea Grant Program, 1974.

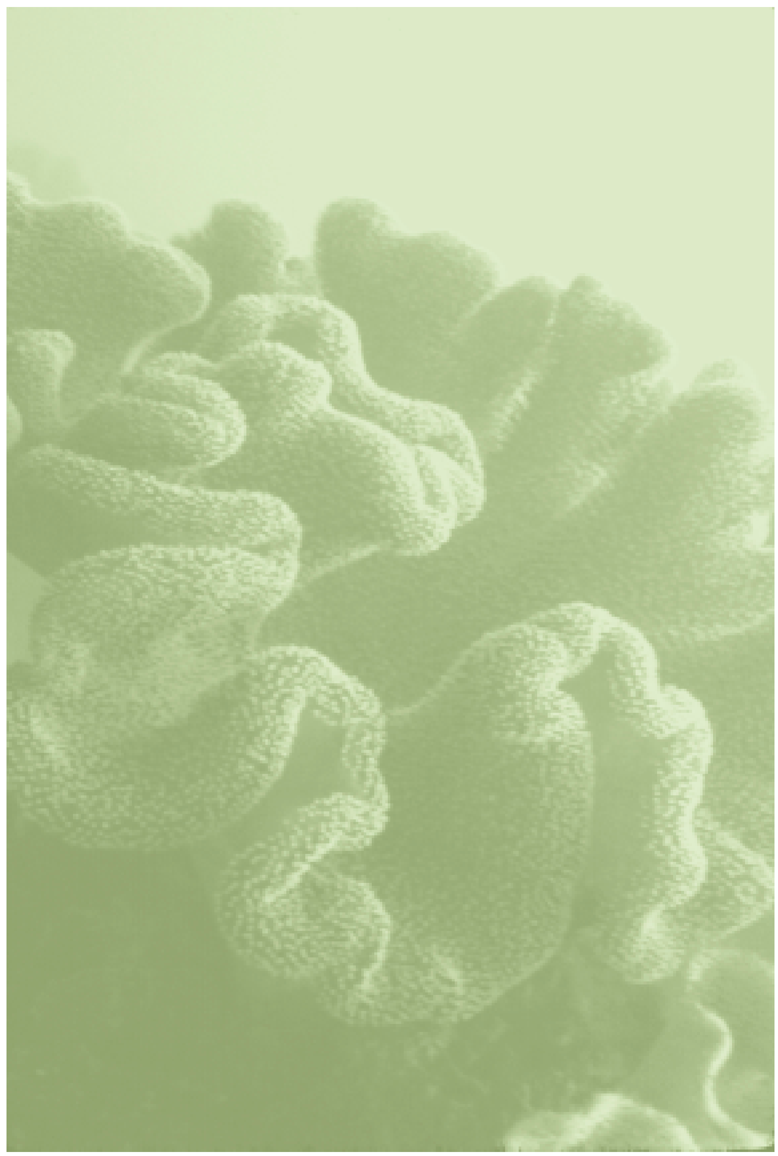


Table of Contents

Executive Summary

Coral reefs appear to be the first major ecosystem type to show rapid degradation at a global scale due to human impacts. Coral reefs are critically important because:

- They contain the world's largest reservoir of marine biodiversity;
- They provide food security, cultural support and physical protection from storms for approximately 500 million people;
- They are the major natural resource for many countries in the world such as small island developing States;
- They are the basis for one of the world's fastest growing industries – coral reef tourism;
- They are declining rapidly from a range of human pressures; and
- There are already distinct signs of damage resulting from global climate change.

It has been predicted that, unless remedial action is taken soon, we could see the virtual destruction of half of the world's coral reefs within a generation. In response to this crisis, the IGOS Partners agreed to the immediate development of a Coral Reef Sub-theme in anticipation of a broader Coastal Theme to be developed for GOOS and GTOS. This report provides strategic recommendations for improved observations and information for decision-making on coral reefs.

Observations in the coastal zone offer a variety of challenges typically associated when working with land, ocean and atmospheric boundaries and their respective interfaces. These challenges limit the possibilities for collecting both *in situ* and remote data. Coral reefs present particular biological challenges for observations because of their great diversity, the mixed spectral signatures of plant/animal symbioses, and their complex structures generated by biological activity. There are also temporal challenges from the heterogeneous and dynamic variations in coral reef communities over time, requiring long time-series observations with enough frequency to determine the state of health of coral reef ecosystems. While coral reef remote sensing promises to address some of these difficulties, there are institutional challenges to integrating remote and *in situ* observations for coral reef monitoring.

Coral reef users need improved mapping of reefs. This will require the development of similar or harmonized classification systems for reef geomorphology and habitats, research into their functional interpretation, higher resolution imagery to resolve reef features, multispectral imagery able to distinguish between reef habitats and conditions, and new approaches to underwater remote sensing at intermediate scales. For detecting change, long-term monitoring programs are required at multiple sites, using imagery with sufficient spatial and spectral resolution to identify changes in communities, correlating observed changes with oceanographic, terrestrial, atmospheric and climatic trends, and linking present trends with the reconstruction of past trends.

To improve early warning of coral bleaching, the operational NOAA "HotSpots" early warning system should be upgraded with higher resolution satellite sea surface temperature measurements validated by *in situ* instrument platforms. Early warning for other reef-threatening events (turbidity, cyclones, pollution, etc.) should also be developed in collaboration with the user communities. To improve local reef management, information products must be generated on the state of local reefs and the effectiveness of management measures at a cost that local users can afford.

For satellite observations of coral reefs, there are two goals:

1. High spatial resolution (1-5 m) hyperspectral sensors with radiometric sensitivity better than 12 bits for mapping and monitoring ecosystem health, providing at least annual coverage of representative coral reefs, and preferably all reefs.
2. Low resolution environmental monitoring of ocean color, sea surface temperature (1 km, 0.05°C), solar insolation, atmospheric sounding for temperature and humidity profiles and CO_2 measurements of the water, more accurate sea surface salinity, wind scatterometers with more frequent passes near the coast, wave height and direction from Synthetic Aperture Radar (SAR), and altimetry to current standards.

These need to be accompanied by image processing methods able to differentiate reef substrates, a long-term acquisition plan for reef imagery for both annual monitoring of all

reefs and more frequent coverage for specific sites, procedures for emergency imaging and monitoring of reefs subject to unusual stress or rapid change, new hyperspectral sensors able to detect algal accessory pigments indicative of benthic communities, spectral libraries and classifications of coral reef habitats and optical water quality, and further research on the relative importance of spatial resolution, spectral resolution and spectral sensitivity in discriminating reef habitats and community changes.

Improved remote sensing imagery can assist by:

- Permitting the mapping and assessment of large and remote areas quickly;
- Assessing characteristics of reefs that have not been measured before;
- Performing near-real time assessments of the status of coral reefs around the world, thereby alerting governments and agencies to conduct *in situ* verification and targeted research, and if feasible, undertake preventive or remedial action.

A significant effort is needed to integrate satellite remote sensing into coral reef monitoring and modelling programs, complementing and reinforcing *in situ* monitoring and assessment that provide critical *in situ* data, and supporting models to analyze circulation, sediment transport, bleaching-risk and other processes. This will require a strategy to optimize *in situ* information flows from instrument platforms, scientific and volunteer monitoring, and to determine the capacity of integrated information to be generalized over large reef areas. Regional centers able to develop and produce coral reef remote sensing products for users are necessary. One specific need is for new instrument packages for underwater remote sensing able to bridge the observational gap in present technologies. Integrated information will require a strengthened ReefBase as an interactive coral reef information system, improved scientific capacity to analyze and interpret observational information, and an increased use of instrumented monitoring stations on coral reefs.

Institutional requirements for effective and integrated coral reef observations include stable funding for international coordination, the incorporation of coral reef monitoring into operational coastal observing programs and information systems, as well as regular coordination among global, regional and national programs and networks. These requirements are common to the whole Coastal Theme, with some specific applications to coral reefs, and will need to be integrated into GOOS and GTOS. The information system should produce affordable products specific to the regional needs of fishers, the tourist industry, monitoring groups, reserve managers, government agencies, planners and scientists. To aid in this effort, a web-based inventory of sources of coral reef information is also desirable.

Thus the major needs are to:

- Improve coordination and information flow amongst current remote sensing, *in situ* monitoring and modeling players;
- Ensure adequate and sustainable funding for existing monitoring coordination mechanisms and new mechanisms designed to improve information flow;
- Improve data management and exchange mechanisms and ensure sustainable funding to the relevant key institutions and programs;
- Develop capacity in remote sensing and *in situ* monitoring to respond rapidly to reporting of unusual events on coral reefs;
- Develop a high spatial and spectral resolution capacity to assess coral reef community changes;
- Develop the capacity to map and monitor coral reefs remotely at the finer scales needed to match *in situ* monitoring *e.g.* 1 to 5m.

The recommended near-term observing requirements, integrating both remote and *in situ* technologies, are summarized in Annex 2.

The report concludes with discussions of the relation of the coral reef sub-theme to other themes and programs, and of institutional responsibilities for its implementation.

The Challenge of Observing Coral Reefs

Report to the IGOS Partnership from the Coral Reef Sub-theme Team

Justification for Coral Reef Sub-theme

Color composite image of Middle Island in the Keppel Islands group, Great Barrier Reef, Australia, formed with radimetrically normalized IKONOS band difference data, Agust 22, 2001.

Coral reefs are one of the most ancient and productive global ecosystem types, and are unique in their construction of major geological features such as barrier reefs and atolls through biological activity. Coral reefs are also now a significant ecosystem under major threat. Widespread episodes of coral bleaching and mortality are being reported from around the world. The combination of local stresses from overfishing, physical destruction, coastal pollution and sedimentation, together with the growing threat from climate change, may result in permanent degradation of the coral reef ecosystem at a planetary scale. In fact, coral reefs may be the first major biological system to respond to human and global change impacts at this scale and in such a short time.

Perhaps 500 million coastal dwellers in tropical countries depend on reef resources for food and livelihoods. Reefs are a major attraction for the development of the tourist industry, and they are important centers of marine biodiversity. Improving the protection and management of coral reefs, and reversing their decline have become high international priorities. In the face of such rapid, large-scale change, there is an urgent need to improve and coordinate observation capabilities for coral reefs and related coastal ecosystems such as seagrass beds and mangroves, and to integrate space-based and *in situ* observing programs in support of management action.

Coral reefs are also now a significant coastal ecosystem under major threat.

Background

The IGOS Partnership, in its meeting on 8 November 2001, decided to initiate discussions among prospective participants that could lead to the development of a Coastal Theme. The coastal zone presents special challenges for both remote and *in situ* observations because of the land-water and air-water interfaces. Coastal observations also need to integrate the terrestrial, oceanic and coastal components, including land-based activities in watersheds and offshore oceanic processes. Because of the complexity of coastal area types, and the diversity of research and user communities dealing with coastal areas, there is logic in developing the Coastal Theme in steps, starting with a relatively narrow focus on a coherent user community. With the urgency of problems facing coral reef ecosystems around the world, the IGOS Partners approved a Coral Reef Sub-theme as the first step in the launching of strategic planning for a Coastal Theme. The IGOS Partnership approved the development of a Coastal Theme in June 2003, at the same time that it approved this report. That theme will be developed under the leadership of CEOS/NOAA/NASA with key roles also played by GOOS, GTOS and IGBP. This sub-theme will be integrated into the Coastal Theme as it is developed, without pre-empting the recommendations of that theme report. In the meantime, because of the urgency of the issues, the IGOS Partners will begin implementation of the Coral Reef Sub-theme.

UNEP and NOAA agreed to co-lead the preparation of an IGOS Coral Reef sub-theme report. A team of 16 members[1] representing AIMS, CBD Secretariat, CSIRO, GCRMN, ICRAN,

---

[1] Arthur Dahl (Co-leader), United Nations Environment Programme (UNEP) and International Coarl Reef Action Network (ICRAN); Alan E. Strong (Co-leader), National Oceanic and Atmospheric Administration (NOAA); Serge Adréfouët, University of South Florida/Institut de Recherche pour le Développement (IRD); Felipe Arzayus, NOAA; Billy Causey, Florida Keys National Marine Sanctuary; Ned Cyr, Global Ocean Observing System (GOOS), Intergovernmental Oceanographic Commission (IOC); Ed Green, UNEP-World Conservation Monitoring Centre (UNEP_WCMC); Georg Heiss, Reef Check; Tijt Kutser, University of Uppsala, Sweden (formerly CSIRO Office of Space Science & Applications, Australia); John McManus, National Center for Carribbean Coral Reef Research (NCORE), Florida; Peter J. Mumby, University of Exeter, United Kingdom; Jamie Oliver, WorldFish Centre, Malaysia; Brad Opdyke, International Geosphere Biosphere Programme (IGBP), Australian National University; Bernard Salvat, EPHE-CNRS, University of Perpignan, France; William Skirving, Australian Institute of Marine Science (AIMS); Marjo Vierros, Secretariat of the Convention on Biological Diversity (CBD); Clive Wilkinson, Global Coral Reef Monitoring Network (GCRMN), Australia.

IGBP, IOC/GOOS, IRD, NCORE, NOAA, Reef Check, UNEP-WCMC, WorldFish Center, and the academic research and reef management communities was assembled, supported by additional experts, with a balance between remote sensing and *in situ* observing experience.

This MERIS image shows the complex river system inside Casamance, Africa with its heavy discharge into the sea. This scence covers the transition zone between savannah in the north and tropical vegetation in the south. Photo: ESA/Cluster.

The team carried out most of its work by e-mail, in addition to holding partial meetings in the Philippines (April 2001), Mozambique (November 2001), Australia (January 2002) and Mexico (June 2002) taking advantage of travel to other meetings.

The development of the IGOS Coral Reef Sub-theme is a component of the International Coral Reef Action Network (ICRAN), a partnership of international organizations, Regional Seas programs and non-governmental organizations working to reverse the decline in coral reefs (www.icran.org). ICRAN supports the implementation of the International Coral Reef Initiative (ICRI) Framework for Action (www.icriforum.org), and has participated in the preparation of this sub-theme report. The user community for coral reef observations is thus well organized to collaborate with GOOS and GTOS in the coordination and implementation of the sub-theme.

The Coral Reef Sub-theme - Present Status and Challenges

Despite the proximity to the coastal area, coral reefs are relatively inaccessible for observations, and present significant technical challenges in the design of an observing strategy. Among the **physical challenges**, waves, currents and the complex forms of reefs make coastal waters a challenging environment to research or monitor. SCUBA diving and submersibles have made deeper reefs more accessible, but are very time-limited, so that only small areas can be observed with any precision. The air-water interface and problems of light attenuation with water depth limit the penetration of air- and satellite-borne instruments.

"The complex symbioses between plants and animals on the reef mix their spectral signatures, creating special challenges for multispectral analysis."

There are also **biological challenges** to reef observations. The diversity and patchy nature of coral reef communities require high-resolution observations for most biological features, resolutions that are at present difficult and expensive to achieve from satellites through the surface water column. Until recently most widely available satellite imagery produced, at best, 10-30 meter pixels and new higher resolution satellites have 2-4 meter pixels, whereas the most biologically interesting scales on reefs would be 0.5 to 5 meters when studying benthic community structure. The complex symbioses between plants and animals on the reef mix their spectral signatures, creating special challenges for multispectral analysis. The similarity between spectral signatures for coral and seaweed requires that satellite sensors be specifically designed to distinguish between the two. In addition, the major growing surfaces of reefs tend to be vertically rather than horizontally oriented, and may be deeper than remote sensors can penetrate. Only now are new technological advances in remote sensing resolving some of these issues, while others will require coordinated partnerships utilizing new combinations of *in situ* and remote data collection.

Reef observing also presents **temporal challenges**. Because coral reefs are naturally heterogeneous and dynamic in time and space, with significant shifts in populations and coverage at various scales, it is difficult to define coral reef health or to distinguish natural from anthropogenic variability. Long time series observations with a large number of data points are required to define community dynamics and thus to determine if a reef is stable, improving or degrading. Few such data series exist, making it difficult to understand and interpret the rapid changes now taking place on many reefs. While monitoring of coral reefs over time is identified as a high priority user requirement, it will be technically difficult. An observing strategy for coral reefs must address these significant challenges as a priority, and that is the focus of this report.

As with other IGOS themes, some of the most important challenges are **institutional**. In an initial review of the present status of observations of coral reefs, it became apparent that there was a general lack of integration of remote observations and *in situ* monitoring programs. Many scientists researching and monitoring coral reefs have little or no remote sensing experience, and little appreciation of the new potential opening up as technologies improve. Direct reef remote sensing is a growing activity, but only a limited number of reefs have been investigated, and new ecological challenges require constant improvement in the algorithms and data. There is an active group working on satellite and airborne remote sensing of coral reefs, but the process of transferring that experience to the wider coral reef research and management community is slow, particularly in developing countries. Although the number of new users is increasing, the costs of remote sensing imagery, and the lack of the necessary expertise to interpret it and to obtain useful information, are seen as major impediments. At the same time, the rapid development of the Internet is creating new potential to connect data producers and users, to transfer technology, and to distribute observing products more widely at a lower cost. Thus, this coral reef sub-theme report is particularly timely.

Issues for a Coral Reef Observing Strategy

The following challenges and issues require attention from the IGOS Partners. A more detailed review of objectives and user needs for a coral reef observing system is provided in Appendix 2.

Coral Reef User Requirements

Mapping

The most frequent current user requirement is for maps of the extent and distribution of existing reef habitats. Because of the incomplete knowledge of the coral reefs of the world, and the lack of a common definition of "coral reefs", estimates of the world coral reef area vary by an order of magnitude. *In situ* survey methods give only very local data, and the deeper parts of the reef system are particularly poorly known. Quantification of coral reef areas by country and region is still a high priority. Global scale geomorphology mapping is currently in progress by several cooperating institutions and several countries have already updated their maps using consistent technologies and geomorphological classification schemes (*e.g.* Indonesia). However, mapping biotopes (or habitats) is presently conducted on an *ad hoc* basis, and the lack of coordination in defining the features mapped seriously hinders the integration of habitat maps from different sources. In order to relate mapped features to management requirements, further research is also needed on the functional interpretation of mapped biotopes. If mapping is to go beyond the simple presence or absence of coral reefs, satellite imagery with better spatial resolution (0.5-1 m) and/or high spectral resolution (many bands) will be required, with some tradeoff possible between the two. Development of underwater remote sensing instruments would make possible faster mapping at intermediate scales and in deeper water.

The issues are:

1. To agree on a common classification system for reef geomorphological features and biotopes;
2. To research the functional interpretation of mapped biotopes and their importance for ecological processes and resource use.
3. To obtain higher resolution imagery able to resolve reef habitats;
4. To develop sensors with high spectral resolution and processing methods (*e.g.* unmixing, modelling) able to distinguish between reef habitats and conditions.
5. To adapt remote sensing instruments or approaches to vessel-borne and underwater use for observations at intermediate scales.
6. To develop *in situ* sensors capable of greater depth of penetration to enable location and mapping of deeper reefs.

Detecting Change

For management purposes, and to understand human impacts, it is essential to assess and monitor the state or health of coral reefs over time. There is no absolute definition of a healthy reef, so only long-term time series observations can determine if a particular coral reef ecosystem is stable, improving or declining. Only a few locations such as the Australian Great Barrier Reef and the Florida Keys presently have the necessary long-term monitoring programs at multiple sites.

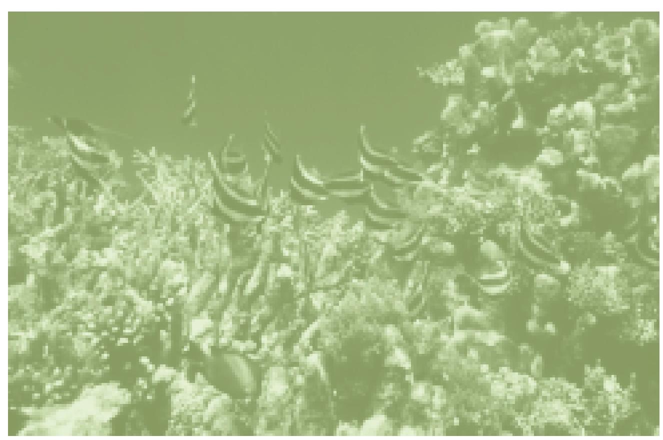
Corals and coral reefs can be recorders of past changes, much like tree ring climate records, documenting paleoclimatic trends, sea levels, and the occurrence of pollutants. These reconstructed time series need to be linked with records in the present to relate them to the current health status of reefs and continuing trends. Any changes detected also need to be correlated with potential driving forces or human impacts.

The factors observed to detect change vary with the nature of the reef and the type of change, with percent live coral cover (or its ratio to recently killed coral) and fish abundance being the most commonly used parameters. Pathological conditions such as coral bleaching, epidemics or algal overgrowth from eutrophication also need to be observed, sometimes signaled by changes in algal pigments. Some parameters may be detectable by remote sensing, while others require *in situ* observations. Given the difficulty to obtain sufficient biological data *in situ* to characterize large-scale phenomena, the challenge to observe significant biological reef changes from satellite platforms has particular importance.

Currently there are no clear mechanisms to link and transfer data from the two scales of monitoring: large scale remote sensing and smaller scale direct *in situ* observation. Direct monitoring is usually conducted by small groups operating through the GCRMN or Reef Check in remote locations in developing countries. In contrast, remote sensing is generally conducted from well-equipped centers in developed countries with excellent communication facilities. There is a need for better communication between the two levels of monitoring to ensure that each is aware of priority needs and able to exchange information on unusual events.

The issues are:

1. To establish monitoring programs at multiple sites generating long-term time series of observations able to establish the state or health of coral reefs at those sites.
2. To develop satellite instruments with the spatial and spectral resolution and the frequency of imagery necessary to observe significant changes in coral reef ecosystems.
3. To correlate observed changes with trends in oceanographic, terrestrial, atmospheric and climatic parameters.
4. To ensure that sensors accommodate other data requirements for reef research and management, including physical variables at appropriate scales such as wave height and direction, water quality, primary production and insolation.
5. To relate present change detection to the reconstruction of past trends as recorded in the corals and reef framework.
6. To develop information transfer mechanisms to ensure a rapid flow of information between the two scales of monitoring; large scale remote sensing and smaller scale direct *in situ* observation.



Heniochus acminatus - butterfly fish. Dr. James McVey, NOAA Sea Grant Program.

Early Warning

As human impacts on coral reefs expand, there is a growing demand for early warning and monitoring of stressful events (SST, turbidity, algal blooms, etc.). NOAA's NESDIS presently provides the only operational information product intended for coral bleaching detection. It is based on sea surface temperature (SST) anomalies as well as the number of weeks that reef areas have been exposed to abnormally high temperatures to identify "HotSpot Bleaching Anomalies", and their accumulations "Degree Heating Week Charts" (DHWs), associated with coral bleaching. Coral reefs are often small areas, less than the present 5-km resolution of SST data. In order for managers and researchers to pinpoint the exact geographic area where a HotSpot is occurring, an increase in the resolution of HotSpot detection is desired (4-km or less). It is possible to distinguish spectral differences between living and recently-dead corals in very favorable conditions, but identifying bleached corals systematically and accurately may require different techniques (*e.g.* unmixing, optimization, modeling, etc.). The Convention on Biological Diversity work plan on coral bleaching includes calls to increase resolution in HotSpot and DHW mapping, to maintain deployment of the relevant sensors, to deploy specialized technology for shallow ocean monitoring, and to make the products of remote sensing readily accessible at low cost to coral reef scientists and managers, especially in developing countries. Such an early warning mechanism will require the integration of diverse data, the development of models to provide advanced warning, and the use of web-based applications to make such early warning systems widely available. Local communities also need increased capacity for validation exercises. The early warning mechanism needs to be accompanied by a rapid response capability.

Other events for which early warning would be desirable include epidemic diseases and population outbreaks, toxic plankton blooms and eutrophication causing excessive algal growth to smother the corals.

The issues are:

1. To raise the resolution of sea surface temperature measurements to 1 km and 0.05°C.
2. To issue automated early watches and warnings of HotSpots for coral bleaching on an operational basis.
3. To explore other events on coral reefs for which observing systems could provide early warning.
4. To establish the necessary *in situ* and remotely sensed instruments and capacity for validation exercises to support the early warning system.
5. To involve the user communities in the development and operation of early warning systems and to strengthen their response capacity.

Local Reef Status

Local coral reef managers are responsible for protected area management, controls on fishing and coastal development, pollution abatement and other actions to protect coral reefs and maintain their productivity. To determine the need for and effectiveness of these measures, they need detailed maps of their coral reefs and continuing data on local stresses, impacts and the effects of protection. While such information products are becoming technically possible, their cost is still far in excess of what local users are able to pay.

The issue is to develop coral reef observing systems able to deliver useful information on local reefs in an affordable, widely accessible and cost-effective way.

True color image of Florida Keys and the Bahamas provided by the SeaWiFS Project, NASA/Goddard Space Flight Center and Orbimage. March, 1999.

Implications for Observing System Design

Optimal Configurations

Quantifying the loss of coral reefs, documenting the health of coral reef ecosystems, mapping reef habitats, and monitoring changes in coral reef ecosystems are essentially the same from a remote sensing point of view. They all require detecting changes in coral reef communities based on differences in optical properties of the benthic habitats.

Image of Louisiana acquired by the LANDSAT 7 Enhanced Thematic Mapper +. Landsat 7's blue band can see some distance into coastal water, which makes silt appear blue as it flows off of the southern coast of Louisiana and into the Gulf of Mexico. The brightness and shade of blue depend on the density of the silt and the depth of the silt-carrying currents in the water.

On many reefs, the most actively growing part with maximum coral cover is on the outer reef slope at depths of up to 15-25 meters. This area is largely out of reach for above water remote sensing because the almost vertical slopes look very narrow from above and because light cannot penetrate so deep. With present image processing methods, the useful depth of light penetration is about 6-7 meters in the wavelength range of 600-750 nm where the differences in reflectance spectra are greatest between different benthic habitats. The depth of penetration is much greater at the blue end of the spectrum (100 m in the case of clear oceanic water), and despite atmospheric correction and instrument calibration problems at this end of the visible spectrum, recent research is revealing areas in the wavelength range 400-600 nm which are also useful for distinguishing bottom types. The practical depth limitation of optical remote sensing for differentiating reef substrates depends on finding appropriate image processing methods, and has yet to be determined. Underwater remote sensing instruments may be an alternative to provide a faster mapping tool than divers' visual observations presently allow (see bridging the observational gap below).

Routine mapping of coral reefs at a geomorphological scale is possible with existing medium spatial resolution sensors (Landsat 5 TM, Landsat 7 ETM+, SPOT HRV, ASTER). There are several regional mapping programs, many reef-scale mapping programs for individual sites, and at least one global scale reef mapping based on ETM+ data. At the present rate, a complete map of the geomorphology and basic habitats of most shallow coral reefs world-wide should be completed in 3-5 years. A coral reef oriented Long Term Acquisition Plan (LTAP) should be designed to schedule systematic global coverage of coral reefs, using ETM+ data supplemented by SPOT, TM and ASTER when necessary, or any future high resolution sensors. Most reefs only require seasonal or annual monitoring. A few identified for permanent monitoring may require weekly monitoring if there are indications of potentially rapid change. Only a few research reefs still being identified by the GEF/World Bank targeted research project may justify periods of daily/weekly monitoring. Temporary monitoring programs could also be designed for specific research purposes. It would be desirable to have the capacity to request emergency monitoring of a coral reef subject to unusual stress or rapid change.

The health of coral reef ecosystems can only be assessed through time, and will require more detailed image acquisitions than for global mapping. The most critical change to capture with remote sensing is from living coral to dead coral (overgrown by different algae). Algal pigments, such as the main photosynthetic pigment chlorophyll a, determine the optical properties of almost all coral reef benthic substrates. For example, the color of living hard and soft corals can be mostly attributed to their symbiotic algae. Thin layers of algae cover dead corals, rubble and even sand particles, and mud can also contain various types of algae. Separating each of these substrates from one another or from seagrasses is only possible by detecting accessory pigments typical to each algal class. For example the zooxanthellae belong to the Dinoflagellates and the typical pigment feature for these algae is the presence of chlorophyll c2, whereas cyanobacteria (covering dead corals) contain phycobiliproteins, etc. The spectral information required to resolve the various substrates has to be obtained with very fine spectral resolution (the pigment absorption bands are often narrow) and through a water column with variable depth and optical characteristics. Similar approaches are needed to distinguish plankton blooms.

Hyperspectral sensors with good spectral, radiometric, and spatial resolution are needed to be able to detect changes in such benthic communities. A sensor with continuous 10 nm bandwidths between 400-1300 nm, with a spatial resolution of 2-10 meters and high sensitivity (12 bits) would meet most requirements. Such sensors would not be limited to one specific application, but could be used for water quality, atmospheric correction and benthic discrimination, with infra-red bands useful for reefs exposed under very low tide conditions and for atmospheric correction. A large number of bands will be required to discriminate the great diversity of reef community configurations world-wide.

Spectral libraries of different coral reef habitats and databases of optical water quality overlaying the reefs have to be collected to study what habitats are separable from each other and to what water depth it can be done. Bio-optical classifications of reef habitats have to be elaborated on the basis of their optical signatures and biological importance. There may be substrate classes that are separable on the basis of their reflectance, but not important from a reef health or ecology point of view. Some important changes in reef habitats may also not be detectable by remote sensing when the habitats are optically not separable.

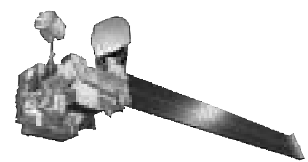
Within-species variability in reflectance spectra of living reef-building corals is very high. Therefore, it is unlikely that remote sensing could be used to detect living corals routinely at the species level. Spectral libraries of coral reef benthic substrates show very high variability in spectral shape and magnitude among similar substrate types. For example reflectance values of sand may be quite different from place to place, and reflectance spectra of living corals differ from each other remarkably in spectral shape and magnitude, etc.

High spatial resolution is needed for many ecological applications, but a suitable signal-to-noise ratio becomes more difficult to achieve without decreasing the spectral resolution. Land sensors (Ikonos, Landsat, ALI) are generally sufficient for shallow water targets. One hyperspectral sensor is presently in space (Hyperion on EO-1), but with only 30 m resolution. It does allow comparison with Landsat imagery to explore spectral vs spatial resolution at several sites.

The relative importance of spatial resolution, spectral resolution and spectral sensitivity in discriminating reef benthos is probably site dependent, scale dependent (landscape, geomorphology, habitat, community) and definitely dependent on the level of precision desired in the classification scheme. However, the wealth of evidence to date suggests that high spectral resolution (at least 6 VIS bands with ca 20 nm width) is essential for mapping benthos and that high spatial resolution with limited spectral resolution proves inadequate for most biological applications.

The requirement of a good coral reef sensor to document changes over time at high spectral and spatial resolution implies other specifications:

- pre-launch calibration and post-launch on-board calibration systems;
- independent vicarious calibration field campaigns on land targets with known atmospheric conditions;
- radiometric stability (bandwidths, band position);
- radiometrically and geometrically calibrated georeferenced products should provide a geodetic accuracy of 12 meters or better, if necessary by using along-track stereo imaging;
- stability of band-to-band registration;
- stability of image-to-image registration.



Advanced Earth Observing Satellite (ADEOS) "MIDORI" is the first international space platform dedicated to Earth environmental research developed and managed by the National Space Development Agency of Japan (NASDA). At 10:53 (JST) August 17, 1996, ADEOS was launched successfully by an H-II Launch Vehicle No. 4, from Tanegashima Space Center (TNSC), and given a name "MIDORI". www.eroc.nasda.go.jp/ADEOS

In summary, the immediate challenges for satellite observations of coral reefs need to aim at two goals:

1. High resolution for mapping and monitoring
   - a. Development of protocols to assess Ecosystem Health
   - b. Hyper 1 meter sensor with on-board calibration
   - c. Multi – non-pointable or Hyper pointable
   - d. Resolution between 1 – 5 meters with calibrated sensors on-board
   - e. Coverage:
   - As a minimum, one cloud free image per year for representative coral reefs and preferably for every coral reef
   - Minimum pass, once a month but would prefer twice monthly
     - Latitudinal coverage: from 35°N to 35°S
   - f. Radiometric Accuracy
     - 12 bits or better
2. Low resolution for environmental research and calibration

Environmental monitoring

- a. Ocean color
  - Improve anomaly-detection algorithms, based on optical values (normalized radiances) or bio-products (pigments, CDOM, sediments)
  - Maintain consistent multi-sensor (CZCS, SeaWiFS, MODIS, etc.) time-series
- b. SST
  - Better spatial resolution. Current resolution on AVHRR sensors on GOES is 4 km. Would like 1 km resolution
  - Accuracy: 0.05° C/0.1° F or better
- c. Atmospheric Sounding
  - Temperature and humidity profiles
  - CO_2 measurements of the water and in atmospheric section
- d. Sea Surface Salinity
  - Need development of more accurate instrument sensors (or local refinement of CDOM/salinity relationships to use ocean color data and algorithms)
- e. Wind scatterometers
  - Near the coast requirements
  - More frequent passes
- f. Altimeters
  - Current sensors are appropriate
- g. Synthetic Aperture Radar (SAR)
  - Current sensors are adequate
  - Algorithms for wave height and direction analysis require improvement

Dr. Anthony R. Picciolo, NOAA NODC, June 1990. Caribean Sea.

The issues are:

1. To develop image processing methods able to differentiate reef substrates at the maximum possible depth.
2. To establish a long-term acquisition plan for reef imagery providing annual or seasonal coverage for all coral reefs, and weekly or even daily monitoring for specific monitoring or research sites.
3. To develop procedures for emergency monitoring of reefs subject to unusual stress or rapid change.
4. To develop and launch hyperspectral sensors with spectral, radiometric and spatial resolution necessary to detect algal accessory pigments and thus to detect changes in benthic communities.
5. To establish spectral libraries and classifications of coral reef habitats and optical water quality.

6. To conduct further research on the relative importance of spatial resolution, spectral resolution and radiometric sensitivity in discriminating reef habitats and community changes.
7. To improve instrumentation and procedures for determining water characteristics important in reef management and research at appropriately fine scales, including waves, productivity, pollutants, sediment load and others, and to develop systematic data acquisition and distribution.

In Situ Observations

In the last decade a series of *in situ* coral reef monitoring programs at regional or global scale have been established. Most of these recommend and use similar methods and protocols that have been shown to provide valuable information on the health status of coral reefs. The scale of monitoring varies from kilometers to meters. Since the methods are all labor intensive, the spatial and temporal coverage is very limited. The potential to complement these programs with remote sensing is very great.

Specific *in situ* observing methods used by scientists and reef managers include manta tow, line transect, permanent quadrat, regional and global biotic and socio-economic indicators, and fish census (Appendix 1A). Parameters recorded comprise a variety of different categories and indicators, like percent cover of live and dead corals, partial coral mortality, size and height, incidence of bleaching/diseases, causes of mortality, coral lifeforms, coral recruits, soft coral, algae, sponges, sediment, and regional specific parameters *e.g.* crown-of- thorns starfish, *Diadema*, giant clams, large patches of damage to corals, major target organisms of the fishers, including indicator species and socio-economic information. The Global Coral Reef Monitoring Network (GCRMN) has recommended the use of the manta tow, line intercept transect using lifeform categories, and visual fish census methods (or equivalent methods) as the baseline for global monitoring.

A significant effort is needed to quality-control, harmonize and integrate the data flows from the different types of monitoring programs.

Simplified coral reef observing methods for use by non-specialists were first developed in the 1970s and have now been standardized by Reef Check. The methods were designed to extract the maximum information about reef health in the minimum amount of time by non-scientist divers.

The recent development by NOAA of the Coral Reef Early Warning System (CREWS) fixed platforms or buoys is initiating the use of *in situ* instrumentation for coral reef monitoring. While these provide continuity and time series data for specific coral reefs that are essential for validation of satellite data, their cost will limit their generalization for other monitoring purposes.

In situ monitoring of coral reefs has largely been ad hoc and driven by scientific priorities rather than management requirements except in a few protected areas. A significant effort is needed to quality-control, harmonize and integrate the data flows from the different types of monitoring programs. Joint strategic planning by all of the principal program organizers would help to optimize the information flow from the different programs and its use for coral reef protection and management.

The time is now ripe for a significant effort to integrate satellite remote sensing into coral reef monitoring and assessment programs. This should make it possible to place field sites in their larger context and thus to extend the results from expensive and labor-intensive field work over much larger areas, supporting more effective management action to respond to the stresses threatening coral reef ecosystems. This will require improved access to remote sensing products, technical capacity building in reef monitoring programs, and targeted financial support, possibly assisted by regional image processing and coordinating centers.

The issues are:

1. To develop a strategy identifying user's present and future needs and optimizing the reef information obtainable from buoys or fixed instrument platforms, scientific monitoring and amateur monitoring to fit those needs.
2. To complement and reinforce *in situ* coral reef monitoring and assessment programs by integrating a remote sensing component.

3. To determine the capacity of integrated *in situ* and remote sensing monitoring to provide data that can be reliably generalized or extrapolated over large reef areas.
4. To establish or reinforce regional centers able to provide remote sensing products in support of coral reef monitoring programs.

Bridging the Observational Gap

This gap in capacity to observe vertical reef faces and deeper reefs over large areas at appropriate scales will require the development of new instruments capable, for instance, of underwater remote sensing perpendicular to the reef slope.

For coral reefs, there is a significant gap between observations possible from satellite and airborne platforms with a maximum resolution of 1-5 meters, and *in situ* observations such as video transects or manta-towed divers. To detect the extent and impact of a coral bleaching event, for instance, or to observe shifts in surface cover from live corals to algae, a resolution of about 10-30 cm would be ideal, requiring new *in situ* or proximate sensing techniques. For satellite sensing, much can potentially be learned with better analytical methods (*e.g.* spectral unmixing) that can retrieve sub-pixel components of coral/algal cover from larger pixels. Research on the latter and on radiative transfer modelling will assist in optical satellite instrument design. Detecting the presence and significance of coral bleaching events will require information also on the percent living coral cover, the amount of recovery of pigmentation after the bleaching event, and the amount of recently dead coral shortly after the event, requiring good time series imagery with a hyperspectral sensor with 4-10 m pixel resolution, unmixing methods and good atmospheric correction. A nested set of observing techniques including satellite remote sensing, intermediate sampling with high-resolution techniques, and traditional *in situ* methods would be ideal for intensively studied areas.

Also, the most significant zone for reef framework development on many coral reefs is the seaward reef face, which slopes steeply and thus appears from the air as a narrow band of widely varying depths. This gap in capacity to observe vertical reef faces and deeper reefs over large areas at appropriate scales will require the development of new instruments capable, for instance, of underwater remote sensing perpendicular to the reef slope.

Another significant need is to be able to detect reefs that are not obvious from the surface. There are probably large areas of coral reefs growing on submerged limestone banks 10 to 50 meters below the surface, which may prove to be important reservoirs of coral and fish larvae for shallow reefs damaged by coral bleaching or overfishing.

Underwater remote sensing instruments should be assembled to be used for independent close range remote sensing, and also for fast ground truthing of satellite data. For diver use or deployment from a small boat or ROV, it is feasible to connect an underwater spectrometer with an underwater laptop equipped with a depth sensor, GPS (through a small buoy attached to the PC), and a digital still or video camera, providing a fully autonomous instrument capable of recording video transects together with reflectance spectra of substrates, coordinates, and depth. An even more useful instrument would have an imaging underwater spectrometer (based on CASI or AISA for example) in the package to cover wider reef areas and to get information about reef structure. Such an instrument should be capable of covering a 10 metre wide band with a resolution of 10 cm, as well as closer video transect work. This would avoid problems of observing across the air-water interface, and, if artificial illumination were incorporated, the problems of light attenuation in the water column.

Such an instrument could provide more detailed information about benthic habitat than just video transects, once algorithms are developed to resolve different substrates on the basis of their reflectance spectra. For more extensive surveys, a similar instrument package mounted on or towed behind a boat, with sonar to measure distance to the reef, could survey extended reef faces at higher speed.

The issue is to fill the observational gap between 10 cm and 4 m resolution, to overcome underwater light attenuation effects, and to survey sloping or vertical reef surfaces, requiring new instrument packages for underwater remote sensing.

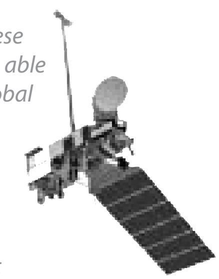
Integration of Remote Sensing and *In Situ* Information

To integrate *in situ* and remotely sensed data, the best tool is a Geographic Information System (GIS). The existing global coral reef database, ReefBase, could evolve into an interactive environmental management information system. Such an on-line GIS should have the ability for "data mining" of all *in situ* data available. Users, scientists and participants in monitoring programs should be able to click on a map and zoom in on their reef from separate layers of satellite images to even include close-up underwater photographs. They should be able to query the health of the reef, input recent data and survey information, and obtain a response in chart format, with management advice on what to do about problems observed. Where possible, these GIS systems augmented with remotely sensed data should be integrated into decision support systems designed to identify the potential consequences of management decisions for reefs and reef-dependent people.

As observing systems improve, there is a growing need for specialist teams of scientists to provide analytical advice on the analysis and interpretation of the observations and to translate the results into management recommendations. In particular, the capacity of scientists in developing countries responsible for reef systems requires strengthening, through education and training programs, and through joint research programs.

The National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch program is installing *in situ* monitoring stations at strategic coral reef areas for purposes of establishing long-term data sets, providing near real-time information products, and surface-truthing NOAA satellite sea surface temperature (SST) products which are used for coral bleaching predictions ("HotSpots") and early warnings. The suite of *in situ* instruments, which transmit data hourly, together with custom artificial intelligence software, are called Coral Reef Early Warning System (CREWS) stations or buoys. The sea temperature sensor data are automatically compared with satellite-monitored temperatures and thus provide near real-time feedback on the accuracy of the satellite-monitored temperatures. The CREWS stations also measure wind speed and direction, air temperature, barometric pressure, sea temperature, and salinity, as well as photosynthetically active radiation and ultraviolet-B above and below the water. Data is presented daily on the Web as well as saved for access via an online database at http://www.coral.noaa.gov/crw.

The Polar Orbiting Satellites (POES) system offers the advantage of daily global coverage, by making nearly polar orbits roughly 14.1 times daily.



Because of the polar orbiting nature of the POES series satellites, these satellites are able to collect global data on a daily basis for a variety of land, ocean, and atmospheric applications. Data from the POES series supports a broad range of environmental monitoring applications including weather analysis and forecasting, climate research and prediction, global sea surface temperature measurements, atmospheric soundings of temperature and humidity, ocean dynamics research, volcanic eruption monitoring, forest fire detection, global vegetation analysis, search and rescue, and many other applications. www.oso.noaa.gov/poes/index.htm

The issues are:

1. To strengthen ReefBase as an interactive coral reef management information system with GIS tools and response capacities to support reef managers.
2. To strengthen programs to integrate a broad range of remotely-sensed products into research, capacity-building and decision-support systems.
3. To build the scientific capacity in the coral reef community to provide analytical analysis and interpretation of observational information in support of management action.
4. To continue to develop instrumented monitoring stations on coral reefs providing data series bridging satellite remote sensing and information from field monitoring programs.

Improved Coordination Among Existing Programs and Networks

Developing early warning systems for coral bleaching and other signs of damage as required by the Convention on Biological Diversity will require extensive coordination among international partners and a significant effort to organize monitoring at the community level. However obtaining funding for international coordination of such operational networks is very difficult. The Global Coral Reef Monitoring Network (GCRMN), closely associated with IOC/GOOS and UNEP, is the existing framework for *in situ* scientific monitoring, while Reef Check provides a similar standard network for surveys by teams of volunteers under scientific supervision. Most coral reef remote sensing has been part of research programs rather than operational monitoring. The NOAA's NESDIS operational remote sensing work on sea surface temperature and coral reef HotSpots, and the Coral Reef Watch stations for a Coral Reef Early Warning System are the beginnings of a near-real-time operational system. ICRI and ICRAN are the principal global mechanisms for coordinating management action on coral reefs. One essential step in a coherent coral reef observing strategy will be to establish mechanisms for regular coordination between these components, both globally and in specific countries and regions.

The issues are:

1. To build global capacity and funding for international coordination through GOOS, including for coral reef monitoring and assessment.
2. To begin to incorporate coral reef monitoring into operational coastal observing programs.
3. To organize regular information exchanges for coordination and strategic planning among global, regional and national programs and networks.

Operational Products and Services

There are several user groups requiring specific coral reef observational products and services:

- **commercial and private entities** that use coral reefs as a source of revenue, such as commercial fishermen and the tourist industry. Tourism is a major economic activity for many developing countries, but too often, for lack of adequate information, it damages the very coral reef resources that help to attract tourists. Fishermen generally become supportive of coral reef management when they see that it ensures the sustainability of their catch.
- **parks, marine reserves** and other areas dedicated to the conservation of coral reefs. Managers and planners need information to maintain and enhance the state of coral reefs under their care, to zone for various uses, and to monitor the effectiveness of management measures.
- **environmental and resource managers** in government and non-profit entities. Managers require information to create and enforce legislation and regulations in order to maintain environmental quality and resource productivity.
- **research and international conservation organizations.** Scientific organizations explore the complex interactions and feedback systems (among others) relevant to ecosystem functions and anthropogenic impacts, as well as reef biodiversity, ecology, pharmaceutical potential, etc.
- **planners.** Government planners (national and local), non-governmental organizations and stakeholder groups need to integrate many kinds of information at various geographic and temporal scales, often in near real-time, with multiple database platforms and Geographic Information Systems.

Geostationary Operational Environmental Satellites (GOES) provide half-hourly observations with two instruments: an imager and a sounder, which measure Earth-emitted and reflected radiation from which atmospheric temperature, winds, moisture, and cloud cover data can be derived. The GOES system serves a region covering the central and eastern Pacific Ocean; North, Central, and South America; and the central and western Atlantic Ocean. Pacific coverage includes Hawaii and the Gulf of Alaska. Two satellites accomplish this; GOES West and GOES East. A common ground station located at Wallops, Virginia, supports the interface to both satellites. www.oso.noaa.gov/goes/index.htm

These groups have different capacities to pay for observing data depending on their informational needs, requiring a careful consideration of the economics of delivering coral reef observations, and particularly of a hyperspectral space mission appropriate for coral reefs. Both public and commercial providers may develop capacities for this, with different costs and advantages. Given the public benefit from better reef management, it would be desirable for image copyrights to be owned by a public or international entity, and for costs to be subsidized or covered systematically for scientists, managers and end-users in developing countries.

For bleaching prone reef areas, a single product combining *in situ* and remote sensed data into **"risk maps" for coral bleaching** is needed (recent results in the Great Barrier Reef are promising). These maps would incorporate general hydrodynamic models of the 'risk' area coupled with HotSpot information as well as other *in situ* or remote sensed products needed for the particular area.

Operational **data processing and management** will be another requirement to be considered. Assuring repetitive global coverage is one thing; providing a mechanism to transfer large amounts of raw data and products to users is another. The characteristics to be included in an effective information delivery system are:

- free scientific use of the data;
- web or hard distribution;
- documentation of algorithms and performance (cal/val experiments);

- free availability of maintained graphic user interface (GUI) software for processing images from raw data into products;
- distribution of beta-products on CDs to users with poor Internet facilities;
- assistance in acquiring necessary computer infrastructure and training.

Given the diversity of coral reefs around the world, regional and thematic optimization of the products will require scientific inputs and controls at all stages. Even for the most routine applications such as geomorphological mapping, classification schemes have to be adapted and optimized to obtain thematically-relevant products from one region to another. Many of the end users who can most benefit from reef observing products may not have the skills and facilities to produce them on their own at the present time. This will require establishing regional facilities for the development, production, distribution and archiving of information products optimized for the region. Four such centers might be appropriate for the Caribbean/Atlantic, the Red Sea/Indian Ocean, South-East Asia, and the Pacific. Remote sensing algorithms can also be developed and automated to enable non-specialists to process images quickly to provide useful information for management use.

Many of the end users who can most benefit from reef observing products may not have the skills and facilities to produce them on their own at the present time.

Consideration will have to be given to the daily data volume generated by the system, and the minimum and maximum extent of coverage, as related to the long-term acquisition plan. Existing regional remote sensing facilities will need to be evaluated for their capacity to handle the amount of data required for change detection analysis on a regional scale, and their ability to produce a line of information products relevant for their regions.

Given the widespread ignorance of the potential of observing systems in the coral reef research and management communities, a web-based **inventory of observational activities**, including sources of both basic and advanced coral reef information, should be established and maintained. This should include the current fleet of operational satellites and their available products, research programs developing new types of observations, and archives, data sources, and public and private entities providing processed information products. Some data for this is being assembled under NOAA-funded projects.

The issues are:

1. To develop specific coral reef information products for fishers, the tourist industry, reserve managers, government agencies, planners and scientists and to establish systems able to make them available at prices the users can afford.

2. To design and establish an information delivery system on a regional basis, with scientific quality control, able to provide appropriate information to reef users and managers.

3. To establish a web-based inventory of sources of basic and advanced coral reef information.

Coral Reef Sub-theme in the Larger Framework

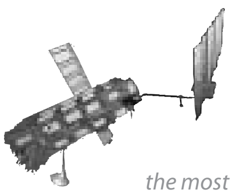
Role in Initiating the Coastal Theme:

Some of the concerns for the coral reef sub-theme touch on generic issues that apply to all coastal areas, and will help to prepare the way for, and ultimately be integrated into, the broader Coastal Theme. These include the approaches necessary to capture essentially linear phenomena along a coastline and the gradients from land to sea, the problems of access across the land/ocean interface and of penetration across the air/water interface, the coastal dynamics of erosion and construction, the importance of detecting the benthos in some detail, and the impacts of land-based activities, pollution, storm damage, sea-level rise, and coastal development generally.

There are also dimensions of the coral reef sub-theme that are quite specific to coral reefs, such as the reef structure generated by biological activity and its morphological evolution relative to the ocean surface, coral bleaching, and the unique spectral signatures produced by the high level of symbioses in reef organisms.

Relation to other themes:

Since coral reefs are affected by oceanic phenomena, several aspects of the **ocean theme** are particularly relevant, including current patterns relevant to larval transport, sea surface temperatures, wind patterns relevant to the movement of excessively warm water masses and resulting coral bleaching, and observations relevant to storm damage. The Global Ocean Observing System (GOOS), responsible for implementation of the Ocean Theme, has just completed its strategic design plan for its Coastal Oceans Observation Module.



Built by a consortium of 50 companies led by Astrium, Envisat is the successor to ESA's ERS satellites. With an array of ten instruments to monitor land, oceans, atmosphere and ice caps, it will provide the most complete set of observations ever achieved, to help scientists understand how changes affect our climate.

The **carbon cycle theme** is particularly significant for coral reefs since anthropogenic shifts in carbon flows may impact reef building. Many reef organisms, both plant and animal, fix calcium carbonate in their skeletons, building reef frameworks into massive geological structures, although healthy reefs are not believed to be significant carbon sources or sinks on short time scales. This calcification process is sensitive to ambient carbon dioxide levels and the pH of surface waters. Rising carbon dioxide is expected to reduce calcification rates of primary reef-building organisms and thus possibly to shift the balance on many reefs from reef construction to reef erosion. Sediment loss from coral reefs to the deep sea is also a poorly quantified dimension of the carbon cycle.

The **water cycle theme** is less immediately relevant, but reefs are sensitive to heavy rainfall and storm runoff lowering the salinity of surface waters, and to the effects of cloud cover on solar radiance. For example, corals shaded during a high temperature episode causing bleaching may suffer less mortality than those exposed to full sunlight.

Relation to other programs:

The IGOS Coral Reef Sub-theme is an important response to the International Coral Reef Initiative (ICRI) Framework for Action, and an integral part of the International Coral Reef Action Network (ICRAN). The recommendations of the Coral Reef Sub-theme report will be considered closely by the ICRAN Steering Committee and those elements relevant to their activities will be integrated into their action programs. The Global Coral Reef Monitoring Network (GCRMN) will also benefit greatly from the more integrated observations resulting from the report, as will the related Reef Check programme. Representatives of ICRAN, GCRMN and Reef Check have all participated in the theme team and support its recommendations.

The Global Ocean Observing System (GOOS) and the Global Terrestrial Observing System (GTOS) both have strong and complementary coastal interests that will be reflected in the IGOS Coastal Theme under preparation, into which the Coral Reef Sub-theme will be integrated. GOOS, through IOC, has also had a representative on the theme team. The work of the Global Climate Observing System (GCOS) is highly relevant to the threats to coral reefs at a global scale from rising carbon dioxide and global warming.

Of the international research programs, the International Geosphere-Biosphere Programme (IGBP) is the one most involved with coral reefs. Its interests are on longer timescales and larger spatial scales than most other reef mapping and monitoring. Much of the IGBP work is concerned with the fluxes of material and elements through various ecosystems and across various geographic boundaries. Work to this end within and around coral reef communities is still in its infancy and does not really lend itself to remote sensing. It will require many hours of ship time, CTD work as well as sediment trap deployment. For example, IGBP is concerned with the amount of calcium carbonate that is swept off reefs into the deep sea and quantifying how much dissolves and how much is buried on the shelf. This sort of work is needed in order to fine tune the details of carbon cycling at the margins of the tropical oceans. Fluxes of this kind are the types of data IGBP would like to tabulate in order to continue to build its global understanding of the carbon cycle.

There will of course be relations with national coral reef programs and agencies too numerous to mention here.

Institutional Responsibilities and Resources for Implementation

Overall leadership and management responsibility in the implementation of the Coral Reef Sub-theme will be shared between the Global Ocean Observing System (GOOS) and the Global Terrestrial Observing System (GTOS) through whatever joint mechanisms they establish under the IGOS Coastal Theme. GTOS will be responsible for the land components relevant to coral reefs in its implementation plan, and GOOS for the ocean components. Under the leadership of these two observing systems, there are a number of existing institutions and programs directly involved in coral reefs that will take responsibility for coordinating and implementing specific components of the Coral Reef Sub-theme. Some of these are IGOS Partners or directly include IGOS Partners in their frameworks and membership; others work closely with one or more IGOS Partners. All of those to whom recommendations have been directed in this report have participated in its preparation.

The International Coral Reef Initiative (ICRI) provides an informal coordination and planning mechanism with regular meetings among all the governmental, intergovernmental and nongovernmental partners concerned with coral reefs. It is the appropriate forum for large-scale global coordination among the organizations involved in sub-theme implementation. Beyond that, partner roles and responsibilities can be broken down into three general categories: observations, data management and product delivery. Within each of these, a variety of partners have participated in the sub-theme development and will be involved in its implementation.

Observations - Observations comprise two components: remote sensing and *in situ*.

For **remote sensing**, NOAA's NESDIS will have lead responsibility for coordinating remote sensing observations identified in the theme report. This will involve coordinating the provision of remotely sensed data from NOAA satellites and other sources. UNESCO/IOC and UNEP will assist by developing MOUs with space agencies for routine provision of data. CEOS will ensure that future satellite missions incorporate coral reef observations into their requirements planning.

There may still be an institutional gap for the interpretation of remote sensing imagery, where work is presently led by individual researchers and research teams. No institution is presently responsible for the coherent development of processed coral reef satellite imagery, its improvement with new technologies, its integration with *in situ* data, and its conversion into operational products. The World Bank/GEF targeted research project includes a remote sensing component that is now providing some coordinated leadership, but there is a need for a more permanent institutional solution.

For ***in situ*** observations, the broad range of institutions involved with coral reef monitoring poses a tremendous coordination challenge. National institutions (*e.g.* NOAA, AIMS, etc.) and scientists in academic or research institutions provide the majority of *in situ* observations of reefs, associated ecosystems and environmental parameters. However the number and diversity of national observing programs makes coordination with individual national programs impractical. There are existing

Mr. Mohammed Al Momany, Gulf of Aqaba, Red Sea.

global coral reef monitoring and observing programs which are coordinating the collection of relevant data from national sources. The Global Coral Reef Monitoring Network (GCRMN), while under-funded, provides a global coordination and assessment mechanism at the scientific level. Under GCRMN a system of regional coordinators is being developed to encourage and guide the development of reef monitoring in the Wider Indian Ocean, Southeast and East Asia, the Wider Pacific Ocean, and the Wider Caribbean and Atlantic Ocean. These should be based in existing institutions to give them access to maximum support. Reef Check is building a complementary network that draws on volunteer support. Together with more regional programs such as CORDIO in the Indian Ocean and AGRA, CARICOMP and NCORE in the Caribbean, there are structures that can potentially be linked into a networked system able to respond to calls for regular or emergency focused monitoring. The GOOS Coastal Ocean Observations Module and the equivalent GTOS Coastal Terrestrial Observations Module can also take responsibility for certain common variables. It will be the responsibility of these programs to coordinate their observations and ensure appropriate global coverage. However none of these activities presently have stable operational funding. All are dependent on donor support that does not assure long-term continuity, and that in most cases is inadequate for the work required.

ReefBase at the WorldFish Center and the UNEP World Conservation Monitoring Centre (UNEP/WCMC) . . . will share the lead for implementing the international data management responsibilities for coral reef information called for in this report . . .

Data Management

- In collaboration with GOOS and GTOS, two institutions will share the lead for implementing the international data management responsibilities for coral reef information called for in this report, in collaboration with national systems such as NOAA's Coral Reef Information System (CoRIS).
- ReefBase at the WorldFish Center (formerly ICLARM) is an operational, on-line, GIS-based global data centre and information system on coral reefs. It is designed to provide relevant data and information to reef managers and scientists, as well as the general public. ReefBase is the data management arm of GCRMN and ICRAN. In implementation of the sub-theme, ReefBase will be responsible for maintaining a global database of coral reef observations, data and information products, including interactive maps with multiple data layers, and providing these through its web site.
- In support of ReefBase, the UNEP World Conservation Monitoring Centre (UNEP/WCMC) has developed digital maps of coral reefs of the world, and will provide these during implementation of the sub-theme. Draft maps have been prepared for all countries, and for 45 countries the reefs have now been mapped at scales of 1:250,000 or better. These maps are available on ReefBase CD and on the Internet (http://www.unep-wcmc.org/marine/data/).

Development and Delivery of Products and Services

Numerous institutions and programs develop, produce and deliver products and services for use by coral reef resource managers, policy makers, commercial and private entities, and the general public. These products include maps depicting coral condition and distribution, reports on global, regional and local coral reef status, and 'HotSpot' warnings.

The International Coral Reef Action Network (ICRAN) is developing an operational structure for action in the field including all the above elements. It is also establishing the framework for regional coordination of coral reef action through the Regional Seas programs.

The Global Coral Reef Monitoring Network (GCRMN), in association with Reef Check, produces a biennial Status of the World's Coral Reefs report, as well as regional status reports.

NOAA/NESDIS uses satellite sea surface temperature imagery to identify 'HotSpot' regions of concern for coral bleaching events, with operational distribution since late 2002 of HotSpot maps and their accumulations, DHWs, at its website (http://www.osdpd.noaa.gov/PSB/EPS/SST/climohot.html).

WorldFish Center (ICLARM) disseminates coral reef information products, including maps, through ReefBase.

The Institute of Marine Remote Sensing at the University of South Florida and other centers maintain image servers to provide images and map products.

The National Center for Caribbean Coral Reef Research (NCORE) coordinates the CARRUS Alliance of research groups from many countries conducting long-term research on reefs and reef-dependent people, and developing decision support systems to integrate remotely sensed data with other information and active scenario-testing models to guide reef management.

IOC/GOOS - Although Coastal GOOS does not presently provide direct observations of coral reefs, it will provide data products which characterize coastal environments and ecosystems in reef areas.

Coral reef observing, while it has some special characteristics, also needs to integrate into observing systems for the whole coastal area, including both the land component which should capture many of the driving forces for coastal degradation, and the ocean component with its strong influence on the nature of and linkages between coastal ecosystems. The Global Terrestrial Observing System (GTOS) and the Global Ocean Observing System (GOOS), already implementing the Ocean Theme for IGOS, should integrate the relevant dimensions of this Coral Reef Sub-theme into their implementation plans in collaboration with the partners identified above, as a step towards the full implementation of the planned Coastal Theme under IGOS.

Conclusions

Much can be accomplished by fully implementing a widely available suite of integrated satellite and *in situ* derived products based on sensors presently available. At the same time, space agencies should consider developing new remote sensors to increase the resolution and accuracy needed to do coral reef monitoring.

Integration of remote and *in situ* sensors is essential to coral reef observations. There are very few *in situ* sensing stations providing near-real-time data, and their number and the coverage of critical reef areas need to be increased. Data assimilation techniques need to be developed that can combine satellite data and traditional field data for coral reef monitoring across the different scales necessary for management action.

The ability to obtain high-resolution imagery of coral reef areas is critical. The present ability to perform multiple scale mapping is limited, expensive and difficult to produce in a timely fashion. The ability to map coral reefs at high resolution in multiple geographical scales would be an asset to reef managers and researchers because it would allow for three-dimensional analysis of coral reefs and for visual confirmation of the health of the reef.

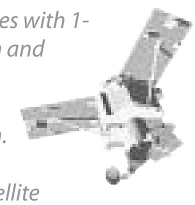
Finally, a high spatial and spectral resolution instrument is required to assess changes in the community structure of affected reefs. An integrated remote sensing program that links physical oceanographic processes (*e.g.* causes of disturbance on reefs) with biological measurements of the consequence of such disturbance (*e.g.* dead coral) would revolutionize understanding of climate-induced phenomena on coral reefs. Furthermore, by identifying physical or biological regions that seem to resist particular disturbances, remote sensing will help governments and conservation agencies prioritize efforts to protect such ecosystems.

Thus the major needs are to:

- Improve coordination and information flow amongst current remote sensing and *in situ* monitoring activities;
- Ensure adequate and sustainable funding for monitoring coordination mechanisms and new mechanisms designed to improve information flow;
- Improve data management and exchange mechanisms and ensure sustainable funding, *e.g.* NOAA's NESDIS and CREWS, ReefBase etc.;
- Develop capacity in remote sensing and *in situ* monitoring to respond rapidly to reports of unusual events on coral reefs;
- Develop a high spatial and spectral resolution capacity to assess coral reef community changes;
- Develop the capacity to map and monitor coral reefs remotely at the finer scales needed to match *in situ* monitoring, *e.g.* 1 to 4m.

The realistic near-term requirements for coral reef observations, integrating both remote sensing and *in situ* technologies and methods, are summarized in Annex 2.

IKONOS is derived from the Greek word for "image." The IKONOS satellite is the world's first commercial satellite to collect black-and-white images with 1-meter resolution and multispectral imagery with 4-meter resolution.



The IKONOS satellite orbits the Earth every 98 minutes at an altitude of approximately 680 kilometers or 423 miles. IKONOS was launched into a sun-synchronous orbit, passing a given longitude at about the same local time (10:30 A.M.) daily. IKONOS can produce 1-meter imagery of the same geography every 3 days.

Products
Standard products include 1-meter black-and-white, 4-meter multispectral (all bands), 1-meter color (true color, false color, or 4-band), and a 1-meter and 4-meter data bundle.

Annex 1A
Current Satellite Missions with Potential Uses for Coral Reef Research

Agency	Sensor package	Platform	Basic Technologies	Currently used products	Potentially useful products
CNES/NASA	TOPEX/POSEIDON	TOPEX/POSEIDON	Radar altimetry	SSH	Wind speed, wave spectrum
CNES/NASA	Jason 1	Jason 1	Radar altimetry	SSH	Wind speed, wave spectrum
CSA/NASA	Radarsat 1	Radarsat 1	SAR	Winds	Ocean roughness, AB, feature tracking, waves
DLR	MOS	IRS-P3	Ocean color		Water quality, solar radiation
ESA	AMI, RA, ATSR & GOME	ERS-2	SAR, scatterometry, altimeter, visible, UV & thermal	SST, SSH	Wind speed, ocean roughness, AB, feature tracking, solar radiation, UV, waves
ESA	GOMOS, MERIS, ASAR, AATSR, RA-2	Envisat	SAR, scatterometry, altimeter, visible (ocean color), UV & thermal	(products not available at time of collation)	Wind speed, ocean roughness, AB, feature tracking, solar radiation, UV, SST, water quality, chlorophyll, waves
CNES	SPOT	SPOT	Visible	Reef mapping/monitoring	SST, solar radiation
EUMETSAT	MSG 1, 2 & 3	MSG 1, 2 & 3	Visible and thermal		
NASA	QuickSCAT	QuickSCAT	Scatterometry	Wind speed & direction	
NASA	ASTER, CERES, MISR, MODIS	Terra	Visible (ocean color) and thermal	Water quality	Reef mapping/monitoring, SST (medium and high resolution), solar radiation, chlorophyll, AB, CDOM
NASA/Orbimage	SeaWiFS	Orbview-2	Ocean color	Water quality, chlorophyll, AB	Solar radiation, CDOM
USGS	ETM+	Landsat- 7	Visible, thermal	Reef mapping/monitoring	
NASA/NMP	Hyperion, ALI, LAC	EO-1	Visible	Reef mapping/monitoring	Water quality, chlorophyll, CDOM, bathymetry
NASA/NASDA	TRMM, CERES	TRMM	Passive microwave, visible and thermal		Rainfall/runoff (fresh water input), solar radiation, SST
NASDA	GMS	GMS	Visible and thermal		Solar radiation and SST
NOAA	Imager and Sounder	GOES 8-12	Visible, thermal		SST and solar radiation
NOAA	AVHRR, SBUV	POES (NOAA 15, 16)	Visible, thermal, UV	SST	Solar radiation and UV
NOAA/NRL	WindSat	Coriolis	Scatterometery	Wind speed and direction	
CNSA	FY-1C	FY-1	Visible, thermal	SST, water quality	Solar radiation
Space Imaging	IKONOS	IKONOS	Visible	Reef mapping/monitoring	
DigitalGlobe	Quickbird	Quickbird	Visible		Reef mapping/monitoring
SAC-C	MMRS	CONAE	Visible		Reef mapping/monitoring

Annexes

1. Tables of current (1A) and future (1B) satellite missions/coral reef parameters
2. Table of recommended requirements for coral reef observing

Appendices

[These appendices are not part of the IGOS Coral Reef Sub-theme Report itself, but contain additional information useful for its implementation.]

1. *In situ* components of coral reef monitoring
2. Detailed objectives and user requirements for coral reef observations, including for the Convention on Biological Diversity
3. References

Dr. Anthony R. Picciolo, NOAA NODC, June 1990. Caribean Sea.

Annex 1B

Future Satellite Missions with Potential Uses for Coral Reef Research

Agency	Sensor package	Platform	Basic Technologies	Potentially useful products
CNES/NASDA	Polder-2	ADEOS-II	Polarized visible/near infrared	Water quality
CNES	SMOS		Microwave imager	SSS
CSA	Radarsat 2	Radarsat 2	SAR	Winds, ocean roughness, AB, feature tracking, waves
EUMETSAT	EPS METOP	EPS METOP	Visible, thermal, scatterometry, radar altimetry	SST, wind, solar radiation, UV, SSH
CAST/INPE	CBRS-2	CBRS-2	Spectrometry	Reef mapping/monitoring
BNSC	GANDER	GANDER	Radar altimetry	SSH, Wind/waves
BNSC	TOPSAT	TOPSAT	Visible	Reef mapping/monitoring
NASA/NASDA	Seawinds	ADEOS-II	Scatterometry	Wind speed and direction
NASA	GPM	GPM	Passive microwave	Rainfall runoff (freshwater input)
NASDA	GLI, AMSR	ADEOS-II	Visible (ocean color), thermal, passive microwave	SST, water quality, chlorophyll, CDOM, solar radiation, AB, rainfall runoff (freshwater input)
NASDA	AVNIR-2, PALSAR, PRISM	ALOS	Visible and SAR	Reef mapping/monitoring, wind speed/direction, waves, ocean roughness, feature tracking
NOAA	VIIRS, CMIS, OMPS	NPOESS	Visible (ocean color), UV, thermal, microwave imagery/sounding	SST, water quality, AB, rainfall runoff (freshwater input), solar radiation, UV, wind speed/direction
CNSA	FY-1D	FY-1	Visible, thermal	SST, water quality, solar radiation
CNSA	HY-1		Visible (ocean color)	Water quality, solar radiation, AB, Chlorophyll
Orbimage	Orbview-3	Orbview-3	Visible	Reef mapping/monitoring
NSPO	ROCSAT-2	ROCSAT	Visible	Reef mapping/monitoring

Annex 2
Recommended Requirements for Coral Reef Observing

Requirement	Resolution	Min. Res	Obs Cycle	OC Min	Avail.	Avail. Min	Accuracy	Acc. Min
Sea Surface Temperature	200 m	1 km	24 h	48 h	1-3 h	3 h	0.1 K	0.5 K
Reef Chlorophyll	200 m	1 km	1 d	3 d	3 d	7 d	5 % (Max)	30 % (Max)
Photosynthetically Active Radiation (PAR)	1 km	5 km	0.04 d	1 d	3 d	7 d	5 % (Max)	20 % (Max)
Sea Surface Height	1 km	5 km	10 d	30 d	3 d	7 d	2 cm	30 cm
Wind Speed/Direction	2 km	10 km	24 h	48 h	1-3 h	3 h	0.5 m/s, 5°	2 m/s, 20°
Wave Height	1 km (near Reef) 10 km (oceanic)	10 km	1 d	3 d	7 d	30 d	*	*
Wave Direction	1 km	10 km	1 d	3 d	7 d	30 d	10°	30°
Reef Sea Surface Salinity	1 km	100 km	8 d	30 d	10 d	30 d	0.1 PSU	1 PSU
Temperature and Humidity Atmospheric Profiles	1 km horizontal, 500 m vertical	10 km horizontal, 1 km vertical	24 h	48 h	1-3 h	3 h	0.1 k, 5% RH	0.5 k, 20% RH
Carbon Dioxide (bulk or surface)	30 km	250 km	6 d	24 d	30 d		*	*
High Resolution Imagery (color hyperspectral)	1 m spatial, 5 nm spectral	10 m spatial, 20 nm spectral	3 d	12 d	10 d	30 d	16 bits	12 bits
High Resolution Imagery (PAN)	30 cm	1 m	3 d	12 d	10 d	30 d	16 bits	12 bits
Reef Geomorphology	5 m horizontal, 30 cm vertical	10 m horizontal, 1 m vertical	1 yr	5 yr	10 d	30 d	10 m	20 m
Benthic Biotopes	50 m	2 m	90 d	1 yr	10 d	30 d	50 cm	5 m
Percent Cover of Live Coral, Stressed/Bleached coral, Recently Dead Coral, Fleshy/Turf algae, Substrate	10 cm	50 cm	0.5 yr	1 yr	10 d	30 d	5 %	10 %
Abundance of Fish, Invertebrates	5 m	10 m	0.5 yr	1 yr	10 d	30 d	5%	10 %
Reflectance Spectra of Substrates	10 cm spatial, 5 nm spectral	5 m spatial, 20 nm spectral	90 d	1 yr	10 d	30 d	16 bits	12 bits

** Waiting for parameters from ENVISAT's SCIAMACHY instrument*

Appendix 1A

In Situ Components of Coral Reef Monitoring

Manta Tow (or equivalent)

Broad scale monitoring (Manta tow, or a timed swim) is needed to:

* develop a broad picture of the reef;
* observe unusual phenomena (like blast damage, plagues); and
* ensure that more detailed monitoring sites are representative of the whole reef.

The Manta tow has been successful in many areas, and consists of 2 minute snorkel tows (minimum of 9) behind a boat at slow speed with stops to record percent cover of live and dead corals, soft coral, and regional specific parameters *e.g.* crown-of- thorns starfish, *Diadema*, giant clams, large patches of damage to corals. These tows are used to select the transect monitoring sites to ensure that they are representative of the whole reef.

Line Intercept Transect or Equivalent

This major monitoring method assesses live coral, preferably with an estimation of coral types, dead coral cover and sand, algae etc. All lifeforms and species must be capable of being compared statistically. Several lifeforms or species can be grouped into larger groups.

Similar techniques, like belt and video transects, are comparable and can be inter-calibrated with the lifeform transects with little difficulty to provide baseline data.

Transects should be placed where coral density is highest *e.g.* 3 to 6 m depth and then used for fish census counts. If possible another set of transects can be done at 10 m depth.

Live Fish Census

Live fish visual censusing is also based on line transects, with fish assessed in a column 5 m wide and 5 m high above the line (less in waters with poor visibility). The initial focus is on counting all fish, especially those that are the major target of the fishers, and possibly including some indicator species like the Chaetodonts.

Permanent Quadrat

If time permits, monitoring teams are encouraged to establish permanent, marked quadrats (*e.g.* 1 m^2) which are assessed regularly, either by photography or mapping to measure growth rates of corals and results of inter-specific interactions. Quadrats are particularly used to follow new coral recruits to determine the ability of a reef to recover from stress. A very important site for monitoring will be reef areas that are almost bare of corals *e.g.* reefs that have been damaged (storms, blast impacts, ship wrecks, fresh water flows, pollution, sediment damage).

Additional components

The installation of semi-permanent low-cost dataloggers for SST and irradiation at selected monitoring sites could be of great use for ground truthing of satellite data, particularly in regions with high cloud cover. The network of monitoring teams (*e.g.* GCRMN, Reef Check, AGGRA, CORDIO) could be used to deploy and service the loggers, collect and submit the data to regional or global (ReefBase) data centers. In this way high quality data can be collected from hundreds of reef sites at very low cost to calibrate and complement satellite derived data.

Reef Check Protocol

The Reef Check protocol for surveys and data collection by volunteers under scientific supervision includes the collection of four types of data: a site description including 37 questions and additional anecdotal and historical information; a fish survey; an invertebrate survey; and a substrate survey. The underwater surveys are made along two depth contours, 2-6 and 6-12 m. For some fish, size limits are used to limit the work load and focus data collection on the target size. The same belt transect is used for each of the surveys.

Appendix 1B

NOAA's Coral Reef Early Warning System Stations

The National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch program is installing *in situ* monitoring stations at strategic coral reef areas for purposes of establishing long-term data sets, providing near real-time information products, and surface-truthing NOAA satellite sea surface temperature (SST) products which are used for coral bleaching predictions ("HotSpots"). The necessary companion chart NOAA produces along with the HotSpots is its Degree Heating Weeks (DHWs) that accumulates these HotSpots over time to indicate regions where thermal stresses are most severe. The suite of *in situ* instruments, which transmit data hourly, together with custom artificial intelligence software, are called Coral Reef Early Warning System (CREWS) stations. At each CREWS station a critical part of the effort is the local maintenance and calibration of the sea temperature sensor to ensure quality data; data can then be automatically compared with satellite monitored temperatures and thus provide near real-time feedback on the accuracy of the satellite-monitored temperatures. The local maintainers also give critical feedback on the presence and progress of coral bleaching and thus validate coral bleaching predictions made by HotSpot and CREWS information products. The CREWS stations slated for deployment in the Caribbean, initially at domestic locations, will also measure wind speed and direction, air temperature, barometric pressure, sea temperature, and salinity, as well as photosynthetically active radiation and ultraviolet-B above and below the water. These environmental variables are important to local bleaching and other biological manifestations (*e.g.,* spawning, migrations), but are also valuable in helping to assess the effect of global climate change on local reefs.

In the Pacific, NOAA is implementing a CREWS buoy, designed to be a permanent installation. The Pacific buoy designs have the advantage that they can be deployed in the Pacific at more remote sites where maintenance is often difficult and where a permanent station cannot be easily installed. As presently configured, they are portable and relatively easy to deploy, and use Argos for their satellite relaying capabilities (thus reducing power requirements, among other considerations). The permanent stations (re-designed to be much sleeker than earlier prototypes) have the advantage that they do not have to be swapped-out every year or two, utilize GOES satellite transmission which is powered by solar panels, and offer fixed orientation for the light sensors (among other considerations, such as tide level), and will serve as an appropriate platform for Web Cam deployment. Permanent stations require occasional maintenance for the light, salinity and other oceanographic sensors. Both types have above and below water light (PAR and UV) sensors, as well as those for air temperature, wind speed and direction, barometric pressure, sea temperature and salinity. All data from both stations will be presented on the Web as well as saved for access via an online database (raw and quality-controlled data). NOAA's current Web site for the daily data is at http://www.coral.noaa.gov/crw.

NOAA's National Marine Fisheries Service (NMFS-Honolulu Lab) deployed several CREWS stations in the NW Hawaiian Islands (2001) and more recently American Samoa (2002). NOAA's Oceanic & Atmospheric Research Atlantic Oceanographic and Meteorological Labs (OAR/AOML) have deployed their initial CREWS test site at Lee Stocking Island, Bahamas, (National Underwater Research Program - NURP) and will be deploying the first Caribbean domestic installation near Salt River Bay, St. Croix, in mid-2002. Plans for the second Atlantic site are still being evaluated. If not at St. Croix, NOAA hopes to install a Web Cam at one of these early Caribbean CREWS installations, in addition to the standard sensors, and is considering making pCO_2 a component at future sites.

These CREWS stations serve several important functions. Primarily, they continue and enhance time-series of environmental indices for coral reefs, making them available on-line over the Internet for early warnings. Quality *in situ* data serve as "anchors" or benchmark calibrations for satellite remotely-sensed data, providing scientists and reef managers in the region high confidence in extrapolations possible from remotely-sensed information throughout the entire region. Often, in tidally active regions, remotely-sensed data coupled with CREWS data, and the much higher temporal resolutions possible through *in situ* means, will provide valuable insight on point variabilities at the CREWS station. This has been documented at the Lee Stocking site, as local investigators were able to use the "Rainbow Gardens" hourly data to determine local "bank" SSTs during ebb tide and "sound" SSTs at flood tide – the local currents drawing waters from those respective locations where satellite observations of SST matched the flow past the CREWS station.

Appendix 2

Detailed Objectives and User Requirements for Coral Reef Observations

Mapping

The most frequent current use for reef observations is to map the extent, distribution and loss or gain of reef habitats over time. At the largest scale, the total area covered by coral reefs is still uncertain. Present estimates of world coral reef area range from less than 0.3 to 3.9 million sq. km. This order of magnitude difference is due to incomplete knowledge of all coral reefs in the world, and to data sources varying from simple charts to remote sensing imagery. It also reflects the lack of a common definition of "coral reefs", whether narrowly determined as hard substrate covered by reef-building calcified organisms, mainly scleractinians, or more widely as the whole coral reef ecosystem with hard and sand substrates. The most accurate recent assessment of coral reef area, in the *World Atlas of Coral Reefs*, used data largely from shallow reef areas, which are more easily charted, but not for deeper parts of the reef system.

There is a need to adopt a common classification of reef geomorphology and of biotopes (or habitats) within geomorphological classes. Geomorphological structures such as outer slope, outer reef flat, spillway, lagoon structures, and pinnacles are functionally important, for example, in their role in building a reef framework. A similar need exists at the finer biological scale of biotopes. Much biotope mapping has been conducted on an ad-hoc basis and often with little information on the derivation and description of the characteristics of each biotope class. This lack of coordination seriously hinders the integration of habitat maps originating from different data sources or organizations. Unless, the categories are clearly described, for example with quantitative descriptors of characteristic features, it is difficult to know which biotope categories are synonymous and which are not. These sorts of inter-map calibration issues are likely to become more important as government, non-profit and conservation agencies move to larger-scale transboundary projects. In short, habitat or biotope classes should be described as clearly as possible. Further, each of these biotopes and geomorphological classes needs to be quantified per country and per region, in order to understand the structure of the world's coral reef ecosystems.

Perhaps one of the most important areas for further research is the functional interpretation of mapped biotopes; what do they tell us about the ecosystem and conservation issues? For example, what do such maps reveal about patterns of productivity or essential fish habitat? To what extent can ecological processes (*e.g.* predation, herbivory) be given a spatially-explicit dimension through the use of biotope maps? How will such information lead to better design of marine reserve networks? Addressing these issues, through multi-disciplinary research, will undoubtedly raise the value of biotope maps as an informative management tool.

Mapping reef geomorphology and biotopes, and estimating their areas, is an objective at all scale levels. At small scale, *in situ* observations can provide the necessary information. Larger scales require interpretation of aerial

Vase sponge with star coral inside. Commander William Harrigan, NOAA Corps (retired). Florida Keys National Marine Sanctuary.

photography. Satellite imagery with existing 20-30 m resolution is available at least for shallow reefs, which are visible globally on a standardized basis but with limited usefulness. A better 0.5-1 m resolution will be required, presently obtainable only with airborne sensors or only recently from higher resolution satellite instruments such as IKONOS with 4m data. Recent work has shown that high spectral resolution (many bands) is perhaps more important for distinguishing reef substrates than high spatial resolution. This is not surprising given that differences in spectra between some reef substrates are subtle and require sophisticated spectral measurements to unravel. Moderate resolution hyperspectral satellite sensors (*e.g.* Hyperion, 30 m pixels) provide valuable spectral data, but new unmixing methods are required to determine the composition of submerged habitats within individual pixels. Such unmixing will become easier with smaller pixel sizes. An optimal satellite sensor would probably have 10 m pixels (or smaller) and at least 10 bands within the spectral range (400 nm - 700 nm). An alternative or supplementary sensor would work *in situ*, underwater. This sensor would detect the specific algal pigments of these different substrates. Underwater remote sensing instruments will need to be developed to provide faster mapping tools at intermediate scales than divers' visual observations.

Detecting Change

For management purposes, and to understand human impacts, it is essential to observe the state or health of coral reefs over time, the impacts of global change, and the consequences of large-scale events.

Generally, the health of coral reef ecosystems cannot be assessed from observations at a single point in time. A long-term series of observations through monitoring programs at multiple sites is required to show if significant parameters are increasing, decreasing or stable. One exception would be when the coral cover approaches or is 100% of the substrate. Without some historical perspective, the maximum values for various parameters, and what constitutes "health", cannot be determined.

Corals and coral reefs can also serve as recorders of past changes that permit hindcasting. Some corals have seasonal growth bands, trap sediments in their skeletons, or preserve isotope ratios in skeletal materials, and reefs themselves record population changes in their accumulated frameworks. Coring samples from corals and reefs can give us an insight into the recent past (Pleistocene), including paleoclimatic trends and sea levels, and the occurrence of pollutants. These time series need to be linked with continuing records in the present to relate them to the current health status of coral reefs and determine if there are any continuing trends.

It is also necessary to observe the present states and significant trends in various environmental parameters (oceanographic, atmospheric, climatic and terrestrial) where anomalies can prove useful in interpreting and even predicting changes in coral reef ecosystems.

A shallow water reef scene. Mike White. Florida Keys National Marine Sanctuary.

Assessment of the health of coral reefs may include qualitative and quantitative data on all biotic components of the ecosystem. However the major components are scleractinian corals (and calcareous algae) and fishes, the first because they are the reef builders and the last for their ecological and economic importance and their role as indicators of human impact. The choice of other biotic components relates to their local importance (sponges, soft corals, molluscs, crustaceans, etc.) or focuses on organisms participating in the degradation of reefs (fleshy algae, sea urchins, etc.). Percent coral cover and fish abundance are usually the most pertinent parameters selected. Optimum values will differ from one region to another, from one reef type to another, and from one habitat to another.

For example, in French Polynesia, research suggests that the most important part of the coral reef ecosystem is the outer slope at a depth of 15-25 meters with 45 to 55% maximum coral cover. But on the deepest hard substrate of this outer slope, where such substrate exists, some observers report maximum cover ranging up to 90%. On the outer reef flats of atolls it is less than 10%. In other regions, countries and habitats, these optimum values for the parameters of health will be different. In other words, a percent coral cover of 40% can indicate very good health at one site but poor health at another; the percent coral cover has little significance in terms of health without knowing the optimum value in that area or habitat. In some cases, a single optimal value may not exist because of natural fluctuation in the measured variable. In these cases, the health of a coral reef must be assessed by examining how changes in key parameters relate to known human impacts or trends in human activities. These parameters of reef health can presently be observed only with *in situ* methods such as reef transects and fish counts. Research should explore whether changes in living coral cover can be observed and quantified remotely with sufficient accuracy, and what technologies might make this possible.

To determine the health status of coral reefs according to their geographical situation, the coral reef ecosystem of each region and country should be divided into a number of geomorphological types and many long-term monitoring surveys should be used to establish optimum values for key parameters. Simultaneous monitoring of human-induced stress such as pollution, sedimentation or destructive fishing should also be carried out. This recommendation is for monitoring programs and especially for International Coral Reef Action Network (ICRAN) selected sites.

Determining optimum values for different coral reef habitats in different regions is only one way to assess the health of any part of any coral reef anywhere. The ratio of live to recently killed coral is an important indicator of changes in reef health, which explains why long-term monitoring is essential. In addition, by documenting size classes of representative organisms (invertebrates and fish) present on reefs, a population trajectory can be determined and predictions made regarding future health.

A second approach to reef health is to observe and quantify known pathological conditions or indicators of ecological imbalance, such as coral bleaching or disease, epidemics or die-offs of echinoderms (*Acanthaster*, *Diadema*), algal overgrowth from eutrophication, etc. Some of these conditions or indicators, such as coral bleaching and algal overgrowth, may be observed with high resolution remote imagery, while others require *in situ* observations of the organisms concerned.

Image processing techniques for collecting relevant data and imagery on coral reefs with various sensors should be tested on some reefs which field surveys have shown to have optimum values of the considered parameters and, thus, very good health. It may be possible to detect some observational parameters, which will differ consistently according to good or poor reef health. The best approach will be to succeed in detecting by remotely sensing algal pigments, which are different in scleractinians, sand, dead corals, etc., with the use of high resolution hyperspectral sensors. These methods measure direct changes in the substratum coverage of coral reefs. An alternative method is to acquire a long time series of satellite data and identify areas that have shown the greatest degree of spectral change over time. Although these indirect methods might not reveal how the reef has changed, they do take advantage of the long time series of satellite data (*e.g.* Landsat TM) and prioritise areas for investigation of change.

Satellite observations of this sort have the potential to reveal significant changes in coral reef health, both short-term alterations due to natural variability or human impacts, and the results of longer climate trends.

Early Warning

As human impacts on coral reef ecosystems expand, there is a growing demand for early warning and monitoring of stressful events. This is already becoming operational for warning of coral bleaching events, when stressed corals lose their zooxanthellae (symbiotic algae) or at least demonstrate a lowering of photosynthetic pigments in their zooxanthellae. Bleached corals may recover, but if the stress is too extreme or lasts too long the corals may suffer high rates of mortality. The most frequent recent stressor has been high water temperatures resulting from altered oceanographic features and enhanced by cloudless skies and low water column mixing associated with the El Niño Southern Oscillation (ENSO) and possibly enhanced by global warming. NOAA's NESDIS provides nearly continuous information on sea surface temperature anomalies as well as the number of weeks geographic areas have been exposed to abnormal temperatures, providing early warning information for "HotSpots" associated with coral bleaching. The companion chart NOAA produces along with the HotSpots is its Degree Heating Weeks (DHWs) that accumulates these HotSpots over time to indicate regions where thermal stresses are most severe.

Other events for which early warning would be desirable include epidemic diseases, damaging population outbreaks (such as the coral-eating starfish *Acanthaster*), toxic plankton blooms and eutrophication causing excessive algal growth smothering the corals.

With expanding and near-continuous monitoring of coral reefs on a near real-time basis, in the future we should be able to identify changes in magnitude and frequency of key environmental variables and their correlation to major damaging events such as coral bleaching. The development of early warning models and effective broadcast networks for the warnings should allow preventive or mitigating measures to be put in place. The user communities should be involved in the development of these early warning systems.

Local Reef Status

Most efforts at coral reef management take place at the local level, and may involve integrated coastal area management, the establishment of marine protected areas, controls on coastal development, anti-pollution measures and fisheries regulations, among others. To determine the need for and the effectiveness of these measures, local coral reef managers need detailed maps of their coral reefs and continuing data on local stresses, impacts, and the effects of protection. While such information tools for local decision-makers are now becoming technically possible, their cost is still far in excess of what local users are able to pay. The challenge is therefore to develop observing systems able to deliver useful information at this scale in a cost-effective way.

Specific User Requirements of the Convention on Biological Diversity

The Parties to the **Convention on Biological Diversity** identified marine and coastal biological diversity as one of the early priority areas for the work of the Convention, as reflected in the Jakarta Mandate on Marine and Coastal Biological Diversity (1995). Decision IV/5 (1998) on the conservation and sustainable use of marine and coastal biological diversity, emphasized the importance of coral reefs. The Conference of the Parties was deeply concerned at the recent extensive and severe coral bleaching, and agreed to integrate coral reefs into its programme of work. This concerned two sub issues: (i) coral bleaching, and (ii) physical degradation and destruction of coral reefs. There are three identified needs and activities in the coral reef work plans that would benefit from remote sensing technologies and integrated observing. These sections are: (1) assessment and monitoring; (2) early warning systems for coral bleaching; and (3) rapid response capability to bleaching.

1. Assessment and Monitoring

The work plan on physical degradation and destruction of coral reefs calls for the provision of a comprehensive analysis of the status and trends of global coral-reef ecosystems. Such an analysis will require the use of remote sensing data at a number of scales in conjunction with field verification. A global assessment of the location and extent of reefs could use lower resolution data. However, an analysis of status and trends would require data that is of high enough resolution to be used in change detection, particularly where the change is indicative of coral reef health, with spectral bands specific to such an analysis. The integration of field verification data, possibly collected by underwater video, with the higher resolution satellite data would also be desirable, though undoubtedly complex.

The work plan on coral bleaching, in its activity 1(b) calls for "implementation and coordination of baseline assessments and long-term monitoring to measure the biological and meteorological variables relevant to coral bleaching, mortality and recovery, as well as the socio-economic parameters associated with coral-reef services". The implementation of the monitoring component of this activity would also require higher resolution data, with enough spectral sensitivity to distinguish between bleached and healthy reefs. In addition, the activity calls for integration of meteorological data, and, by extension, the integration of oceanographic data. The integration of such diverse data would require sophisticated spatial modeling capabilities. Such activities should be carried out in conjunction with ongoing assessment and monitoring initiatives, such as those of UNESCO, ICRAN, the regional seas conventions and action plans, GCRMN, UNEP and CORDIO.

The coral bleaching work plan also calls for "strengthening networks for data collection and dissemination of information on coral-reef status and interpretation of long-term trends resulting from global climate change and anthropogenic stresses to assist effective management and conservation." Not only should the appropriate data be made available, but also information and conclusions resulting from the analysis of those data should be widely disseminated, in particular for management purposes.

2. Early Warning Systems

The coral bleaching work plan places an emphasis on the importance of early warning systems for coral bleaching. In particular, the work plan includes the following activities:

"Extend the use of early-warning systems for coral bleaching by:

(i) Enhancing current NOAA AVHRR HotSpot mapping by increasing resolution in targeted areas and carrying out ground-truth validation exercises;

(ii) Encouraging space agencies and private entities to maintain deployment of relevant sensors and to initiate design and deployment of specialized technology for shallow-oceans monitoring;

(iii) Making the products of remote sensing readily accessible at low cost to coral-reef scientists and managers worldwide, in particular to those scientists and managers that are based in developing countries."

Steve Turek, Borneo.

This would require higher resolution sensors with appropriate spectral sensitivity for monitoring shallow-water areas, the integration of diverse data, and the development of models that could provide advance warning of impending bleaching events. The work plan supports using web-based applications for making such early warning systems widely available. It also calls for developing local community capacity for remote and local level validation exercises and for developing mechanisms to make accessible high-resolution multi-spectrum imagery worldwide.

3. Rapid Response Capability to Bleaching

The work plan on coral bleaching also calls for the development of "a rapid response capability to document coral bleaching and mortality in developing countries and remote areas including establishment of training programs, survey protocols, expert advice, and contingency fund or rapid release of special project funding." Although some parts of this activity may be beyond the scope of the IGOS coral reef theme, it does highlight the need for capacity building and funding for remote sensing activities.

Appendix 3

References

Andréfouët, Serge (2002), IGOS: Coral reef theme; high resolution mapping and change detection. (paper prepared for the IGOS Coral Reef Sub-theme team).

Andrefouet S. et. al., (in press), Multi-sites evaluation of IKONOS data for classification of tropical coastal environments. *Remote Sensing of Environment.*

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

Arvidson, T., J. Gasch, and S.N. Goward (2001), Landsat 7's long term acquisition plan- an innovative approach to building a global imagery archive. *Remote Sensing of Environment*, **78**: 13-26.

Atkinson, M.J., et al. (2001), *CRESPO: Coral Reef Ecosystem Spectro-Photometric Observatory*, concept study report to the University Earth System Science Program, National Aeronautics and Space Administration, University of Hawaii, 2001.

Atlantic and Gulf Rapid Reef Assessment (AGRRA) Program: http://coral.aoml.noaa.gov/agra.

Berkelmans, R. and J.K. Oliver (1999), Large scale bleaching of corals on the Great Barrier Reef. *Coral Reefs,* **18**:55-60.

Berkelmans, R., and B.L. Willis (1999), Seasonal and local spatial patterns in the upper thermal limits of corals on the inshore central Great Barrier Reef. *Coral Reefs,* **18**:219-228.

Brown, B.E. (1997), Coral bleaching: Causes and consequences. *Coral Reefs,* **16**: S129-S138.

Brown, B.E. and J.C. Ogden (1993), Coral bleaching. *Scientific American*, **268**: 64-70.

Capolsini, P., S. Andréfouët, C. Rion, and C. Payri (in press), A comparison of Landsat ETM+, SPOT HRV, Ikonos, ASTER and airborne MASTER data for coral reef habitat mapping in South Pacific islands. *Canadian J. Remote Sensing.*

Caribbean Coastal Marine Productivity (CARICOMP) Programme: http://isis.uwimona.edu.jm/centers/cms/caricomp.

Causey, B.D. (1988), Observations of environmental conditions preceding the coral bleaching event of 1987—Looe Key National Marine Sanctuary. *In Proc Assoc Is Mar Lab Carib*, **21**: 48.

Dahl, A.L. (1981), *Coral Reef Monitoring Handbook*. South Pacific Commission, Noumea, New Caledonia, 21 p.

Dustan, P., E. Dobson & G. Nelson (2001), Landsat Thematic Mapper: detection of shifts in community composition of coral reefs. *Conservation Biology*, **15**: 892-902.

English, S., C. Wilkinson and V. Baker (1997), *Survey Manual for Tropical Marine Resources* 2nd ed. ASEAN-Australia Marine Science Project: Living Coastal Resources, Australian Institute of Marine Science, PMB No. 3, Townsville, Australia, 390p.

Gleason, D.F. and G.M. Wellington (1993), Ultraviolet radiation and coral bleaching. *Nature*, **365**: 837-838.

Gleeson, M.W. and A. E. Strong, 1994, Applying MCSST to coral reef bleaching, *EOS,* **75**: 156

Global Coral Reef Monitoring Network: http://www.gcrmn.org/ .

Glynn, P. (1993), Coral reef bleaching: Ecological perspectives. *Coral Reefs*, **12**: 1-17.

Goreau, T., T. McClanahan, R. Hayes, and A.E. Strong (2000), Conservation of coral reefs after the 1998 global bleaching event, *Conservation Biology*, **14**(1): 5-15.

Hedley, J.D. and P.J. Mumby (2002), Biological and remote sensing perspectives of pigmentation in coral reefs. *Adv. Mar. Biol.*, **43**: 277-317.

Hedley, J.D. and P.J. Mumby (2003), Spectral unmixing and the resolution of depth from remotely sensed data of aquatic systems. *Limnology & Oceanography,* **48**: 480-488.

Mary Lou Frost, 1995. Egypt.

Hendee, J.C. (1998a), An expert system for marine environmental monitoring in the Florida Keys National Marine Sanctuary and Florida Bay, In *Proc 2nd Int Conf Env Coastal Regions*, ed. CA Brebbia, Computational Mechanics Publications/WIT Press, Southampton, 57-66.

Hendee, J.C., C. Humphrey, and T. Moore (1998b), A data-driven expert system for producing coral bleaching alerts, In *Proc 7th Int Conf Developm Applic Comp Techn Env Stud*, eds. DW Pepper, CA Brebbia, P Zannetti, Computational Mechanics Publications/WIT Press, Southampton, 139-147.

Hendee, J.C. (2000), *A data-driven soft real-time expert system for producing coral bleaching alerts.* Ph.D.Thesis, Nova Southeastern University, 131 pp.

Hendee, J.C., E. Mueller, C. Humphrey, and T. Moore (2001), A data-driven expert system for producing coral bleaching alerts at Sombrero Reef in the Florida Keys. *Bulletin Marine Science,* **69**(2): 673-684.

Hochberg, E., & M.Atkinson (2003), Capabilities of remote sensors to classify coral, algae and sand as pure and mixed spectra. *Remote Sensing of Environment,* **85**(2):174-189.

Hochberg E.J., M.J.Atkinson, and S.Andréfouët (2003) Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. *Remote Sensing of Environment,* **85**: 159-173.

Hodgson, G. (1999), A global assessment of human effects on coral reefs. *Marine Pollution Bulletin,* **38**: 345-355.

Hodgson, G and C.Wilkinson (2001), Science as a basis for coral reef monitoring programs. *Bulletin of Marine Science,* **69**(2): 327-328.

Hodgson, G. and J. Liebeler (2002), *The Global Coral Reef Crisis*, Trends and Solutions, 77 p.

Hoegh-Guldberg, O. (1999), Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshw. Res.,* **50**:839-866.

Hoegh-Guldberg, O., R. Berkelmans, and J. Oliver (1997), Coral bleaching: Implications for the Great Barrier Reef Marine Park. In *Proc Great Barrier Reef Conf,* 24-29 November 1996, Great Barrier Reef Marine Park Authority, Townsville.

Hu C., K.E. Hackett, M.K. Callahan, S.Andréfouët, J.L.Wheaton, J.W. Porter, F.E. Muller-Karger. (2003), The 2002 ocean color anomaly in the Florida Bight: a cause of local coral reef decline, *Geophysical Research Letters,* (in press).

Institute for Marine Remote Sensing, University of South Florida: http://imars.marine.usf.edu/corals .

International Coral Reef Action Network (ICRAN): http://www.icran.org .

International Coral Reef Initiative (ICRI): http://www.icriforum.org .

International Workshop on the Use of Remote Sensing Tools for Mapping and Monitoring Coral Reefs, Honolulu, Hawaii, 7-10 June 1999: http://coral.aoml.noaa.gov/corvil/coral_reefs/index.html.

Jaap, W.C. (1978), Observations on zooxanthellae expulsion at Middle Sambo Reef, Florida Keys. *Bull. Mar. Sci.,* **29**(3): 414-422.

Jaap, W.C. (1988), The 1987 zooxanthellae expulsion event at Florida reefs. *NOAA's Undersea Research Program Research Report,* **88**(2): 24-29.

Jones, R.J. (1997), Zooxanthellae loss as a bioassay for assessing stress in corals. *Mar. Ecol. Prog. Ser.,* **149**: 163-171.

Jones, R.J., R. Berkelmans, and J. Oliver (1997), Recurrent bleaching of corals at Magnetic Island (Australia) relative to air and seawater temperatures. *Mar. Ecol. Prog. Ser.*, **158**: 289-292.

Joyce, K., M. Stanford and S. Phinn (n.d.), *Remote Sensing for Coral Reef Monitoring: What is Required?* Biophysical Remote Sensing Group, University of Queensland, Australia.

Kushmaro, A., E. Rosenberg, M. Fine, and Y. Loya (1997), Bleaching of the coral Oculina patagonica by Vibrio K-1. *Mar. Ecol. Prog. Ser.*, **147**(1-3): 159-165.

Kutser, Tiit, Arnold G. Dekker, William Skirving (2003), Modelling spectral discrimination of Great Barrier Reef benthic communities by remote sensing instruments. *Limnology & Oceanography,* **48**(1, part 2): 497-510.

Lang, J.C. (1988), Apparent differences in bleaching responses by zooxanthellate cnidarians on Colombian and Bahamian reefs. *NOAA's Undersea Research Program Research Report,* **88**(2): 30-32.

Liu, Gang , A. E. Strong, and W. Skirving (2003), Remote Sensing of Sea Surface Temperatures During 2002 Barrier Reef Coral Bleaching, *EOS*, **84**:137-144.

Lesser, M.P., W.R. Stochaj, D.W. Tapley, and J.M. Shick (1990), Bleaching in coral reef anthozoans: Effects of irradiance, ultraviolet radiation, and temperature on the activities of protective enzymes against active oxygen. *Coral Reefs,* **8**: 225-232.

Louchard, E.M., P.R. Reid, C.F. Stephens, C.O. Davis, R.A. Leathers, and V.T. Downes (2003), Optical remote sensing of benthic habitats and bathymetry in coastal environments at Lee Stocking Island, Bahamas: a stochastic spectral classification approach. *Limnology & Oceanography,* **48**(1, part 2):511-521 .

Mockler, R.J. and D.G. Dologite (1992), *Knowledge-Based Systems: An Introduction to Expert Systems,* Macmillan Publishing, New York, 792 pp.

Mumby, P.J., S. Andréfouët, J.T. Hardy, E. Hochburg, E.F. LeDrew, W. Skirving, A.E. Strong, R. Stumpf (2003), Remote Sensing of Coral Reefs and their Physical Environment, Manuscript in preparation.

Mumby, P.J., J.R.M. Chisholm, J.H. Hedley, C.D. Clark and J. Jaubert (2001), A bird's-eye view of the health of coral reefs. *Nature*, **413**: 36.

Mumby, P.J. and A.J. Edwards (2002), Mapping marine environments with IKONOS imagery: enhanced spatial resolution does deliver greater thematic accuracy. *Remote Sensing of Environment,* **82**: 248-257.

Mumby, P.J., E.P. Green, A.J. Edwards and C.D. Clark (1999), The cost-effectiveness of remote sensing for tropical coastal resources assessment and management. *Journal of Environmental Management,* **55**:157-166.

Mumby, P.J., E.P. Green, C.D. Clark and A.J. Edwards (1998), Digital analysis of multispectral airborne imagery of coral reefs. *Coral Reefs,* **17**: 59-69.

Mumby, P.J., and A.R. Harborne (1999), Development of a systematic classification scheme of marine habitats to facilitate regional management and mapping of Caribbean coral reefs. *Biological Conservation,* **88**: 155-163.

National Center for Caribbean Coral Reef Research (NCORE): http:www.ncoremiami.org

NOAA/NESDIS HotSpot maps and DHWs: http://www.osdpd.noaa.gov/PSB/EPS/SST/climohot.html.

Oliver, J.K. (1985), Recurrent seasonal bleaching and mortality of corals on the Great Barrier Reef. In *Proc 5th Int Coral Reef Congr, Tahiti,* **4**: 201-206.

Palandro, D., S. Andréfouët, P. Dustan & F. E. Muller-Karger (2003). Change detection in coral reef communities using the Ikonos sensor and historic aerial photographs. *Int. J. Remote Sensing,* **24**(4): 873-878

Palandro, D., S. Andréfouët, F. Muller-Karger, P. Dustan, C. Hu & P. Hallock (in press). Detection of changes in coral communities using Landsat 5/TM and Landsat 7/ETM+ data. *Canadian J. Remote Sensing.*

Pandolfi, J.M. (1999), Response of Pleistocene coral reefs to environmental change over long temporal scales. *American Zoologist,* **39**: 113-130.

Pandolfi, J.M., G. Llewellyn and J.B.C. Jackson (1999), Interpretation of ancient reef environments in paleoecological studies of community structure: Curaçao, Netherlands Antilles, Caribbean Sea. *Coral Reefs,* **18**: 107-122.

Pandolfi, J.M., J.B.C. Jackson and J. Geister (in press), Geologically sudden natural extinction of two widespread Late Pleistocene Caribbean reef corals, in Jackson J.B.C., S. Lidgard, and F.K. McKinney (eds.) *Process from Pattern in the Fossil Record,* University of Chicago Press, Chicago.

Reaser, J. K., R. Pomerance, and P. O. Thomas (2000), Coral bleaching and global climate change: Scientific findings and policy recommendations, *Conservation Biology,* **14**, 1500-1511.

Reef Check global coral reef education, monitoring, and management program: http://www.reefcheck.org.

Report of AIMS/NOAA Workshop on Satellite Oceanography and Coral Bleaching, Magnetic Island, Australia, 30 January-1 February 2002.

Robinson, J.A., C.A. Evans, and S.K. Krikalev, Six-meters spatial resolution for remote sensing of Earth from the International Space Station. *EOS Trans. AGU*, **83**:185 and 188.

Spalding, Mark D., Corinna Ravilious and Edmund P. Green (2001), *World Atlas of Coral Reefs.* Prepared at the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley, USA.

Strong, A.E., E. Kearns, K.K. Gjovig (2000), Sea Surface Temperature Signals from Satellites - An Update. *Geophys. Res. Lett.,* **27**(11): 1667-1670.

Strong, A.E., G. Liu, J. Meyer, J.C. Hendee, and D. Sasko (2002), Coral Reef Watch 2002. Paper Submitted – *Bull. Marine Sci.*

Strong, A.E., C.S. Barrientos, C. Duda, and J. Sapper (1997), Improved satellite Techniques for Monitoring Coral Reef Bleaching. In *Proc 8th International Coral Reef Symposium,* Panama City, Panama, p.1495-1498.

Sweatman, H., A. Cheal, G. Coleman, B. Fitzpatrick, I. Miller, R. Ninio, K. Osborne, C. Page, D. Ryan, A. Thompson, and P. Tomkins (2000), *Long-term monitoring of the Great Barrier Reef. Status Report (4).* Australian Institute of Marine Science, Townsville, Australia, 117pp.

Wachenfeld, D.R., J.K. Oliver, and J.I. Morrissey (eds) (1998), *State of the Great Barrier Reef World Heritage Area, 1998.* Great Barrier Reef Marine Park Authority, Townsville, Australia, 139pp.

Walther G.R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein (2002), Ecological responses to recent climate change. *Nature,* **416** (6879): 389-395, 28 March 2002.

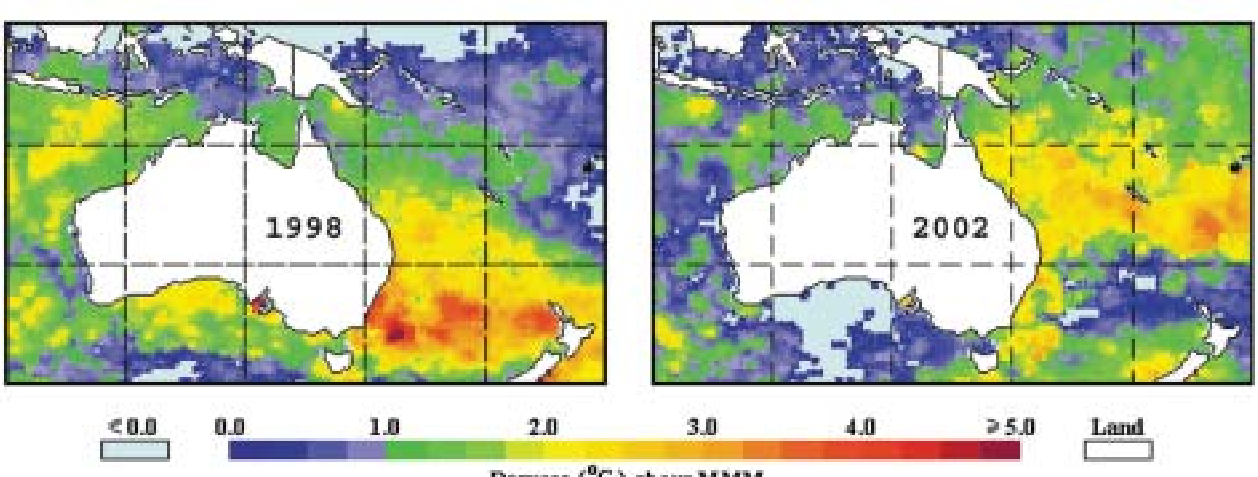
Wellington, G.M., P.W. Glynn, A.E. Strong, S. Navarrete, and E. Wieters (2001), Crisis on coral reefs linked to climate change. *EOS,* **82**(1), 1 and 5.

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**(2), 188-196.

Wilkinson, Clive (ed.) (2002), *Status of Coral Reefs of the World 2002.* Australian Institute of Marine Science, Townsville.

WorldFish Center: http://www.worldfishcenter.org/.

The cover image and all images not otherwise credited are courtesy of the NOAA Photo Library at ***http://www.photolib.noaa.gov/****.*
Cover: Brain coral and sea fan close up. Steven Cook, 1987. Florida Keys National Marine Sanctuary. The photo has been altered using Adobe® Photoshop®.



Composite HotSpot charts of the summer seasons of 1998 and 2002 showing the distribution and magnitude of the maximum composite of HotSpots over the summer (December through March).