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Marine Pollution Bulletin 48 (2004) 219–228
MARINE POLLUTION BULLETIN
www.elsevier.com/locate/marpolbul

Review

Remote sensing of coral reefs and their physical environment

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Abstract

There has been a vast improvement in access to remotely sensed data in just a few recent years. This revolution of information is the result of heavy investment in new technology by governments and industry, rapid developments in computing power and storage, and easy dissemination of data over the internet. Today, remotely sensed data are available to virtually anyone with a desktop computer. Here, we review the status of one of the most popular areas of marine remote sensing research: coral reefs. Previous reviews have focused on the ability of remote sensing to map the structure and habitat composition of coral reefs, but have neglected to consider the physical environment in which reefs occur. We provide a holistic review of what can, might, and cannot be mapped using remote sensing at this time. We cover aspects of reef structure and health but also discuss the diversity of physical environmental data such as temperature, winds, solar radiation and water quality. There have been numerous recent advances in the remote sensing of reefs and we hope that this paper enhances awareness of the diverse data sources available, and helps practitioners identify realistic objectives for remote sensing in coral reef areas.

Keywords: Remote sensing; Coral reefs

1. Introduction

The dynamics of coral reef organisms are affected by a vast range of processes that span scales of millimetres to thousands of kilometres (Hatcher, 1997). If scientists are to understand how such processes interact to structure reef communities, it is vital that observations are taken at appropriate scales and preferably, across a range of scales simultaneously. To understand processes of reef degradation, for example, it would first be useful to obtain a synoptic measure of change in community structure across the entire system. Since field surveys are usually too time consuming and expensive to conduct over a continuum of scales, remote sensing must be used to scale-up field observations. To identify the causes of degradation, it would then be necessary to compile reef-scale data on key disturbance factors and attempt to match the scales of pattern (change in community structure) to candidate processes. Although not all deleterious processes can be measured directly (e.g. overfishing), many environmental and ecological properties can be measured using remote sensing. These properties include sea surface temperature (SST), chlorophyll-a, suspended sediment concentration, precipitation, solar radiation, salinity, wind speed, algal blooms, etc. Given a robust understanding of the ecosystem responses to these environmental parameters and some *in situ* field observations, many other biological benchmarks can often be indirectly derived (e.g. fish abundance).

Developments in sensor technology, data storage and an ever-expanding market for spatial data have led to a bewildering array of remote sensing products. This

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0025-326X/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2003.10.031

paper aims to provide an overview of the state-of-the-art in remote sensing for coral reef management. We focus initially on the attributes of coral reefs that can be measured, generally at several metres to submetre scales using remote sensing. We then provide an overview of the physical environmental variables that can be remotely sensed. The latter are often measured using pixel sizes of kilometres or larger, but observations are taken routinely enabling time series climatologies to be established with maximum temporal resolutions ranging from hours to days, depending on the environmental parameter being measured. Most of the information pertinent to this review is presented in tables and text is only used to elaborate on specific caveats or exceptions.

1.1. What ecological properties of reefs can we measure using remote sensing (Table 1)?

Optical remote sensing methods typically penetrate clear waters to approximately 15–30 m. Light penetration is wavelength dependent, being greater in blue wavelengths (400 nm) than, say, red wavelengths (600 nm). The precise degree of penetration in a spectral band will depend upon the optical properties of the water (e.g. the concentration of coloured dissolved organic matter and suspended sediments). However, a number of workers have capitalised upon the wavelength-dependency of light penetration and proposed methods for predicting bathymetry (e.g. Jupp, 1988; Stumpf et al., 2003). The most recent methods (Stumpf et al., 2003) can be derived from many types of optical imagery (e.g. IKONOS) and accurately reveal patterns of bathymetry on coral reefs to a depth of ≈25 m. Although such maps of bathymetry are not suitable for navigation, they have many uses in hydrological modelling and describing the physical environment of coral reefs (Table 1).

Many coral reefs exhibit a common, distinctive pattern of geomorphologic zonation, which is generally a product of the interaction between reef developmental processes and the oceanic physical environment (Stoddart, 1969). Typical zones include the forereef, reef crest, reef flat, back reef, and lagoon with pinnacles. Because these zones are associated with characteristic depth distributions and benthic community structures, and because they occur at spatial scales of tens to hundreds of metres, they are amenable to remote detection by moderate- (e.g. Landsat Multispectral Scanner, TM, ETM+; SPOT-HRV; ASTER) and a fortiori high-resolution sensors (IKONOS, Quickbird). Indeed, investigation of geomorphologic zonation has proven to be one of the most successful applications of digital remote sensing to reef environments from the earliest days of Landsat (Smith et al., 1975) through to the present (Andréfouët et al., 2001a).

Most coral reef remote sensing has used optical sensors which are of very limited value in high turbidity environments. These limitations are now being overcome through the deployment of acoustic remote sensing methods. Active sonar sensors are usually towed behind a boat and measure the depth of the water and components of surface roughness and hardness (White et al., 2003). Compared to optical methods, these sensors have the following advantages; (i) greater depth of penetration, (ii) unconstrained by optical water properties, and (iii) measurement of sea bed structure, which may be particularly important for specific organisms such as reef fish. However, disadvantages of the methods include; (i) they cannot be deployed in shallow water (<0.5 m), (ii) they do not provide synoptic measurements over large areas and maps usually have to be generated by interpolating between acoustic tracks, and (iii) they are unable to discriminate benthos on the basis of pigmentation (colour). A recent study found that a few coral habitats could be discriminated using acoustic sensors and that map accuracies were comparable to those from Landsat TM (White et al., 2003). There is, however, much scope for combining spectral and acoustic methods.

Moving beyond mapping reef geomorphology, a number of studies have used high resolution instruments to map reef communities (also referred to as habitats or biotopes). The number of classes (categories) distinguishable by remote sensing depends on many factors including, the platform (satellite, airborne, towed instrument) type of sensor (spectral, spatial and temporal resolution) atmospheric clarity, surface roughness, water clarity and water depth. Experiments based on simulation (Hochberg and Atkinson, 2003; Kutser et al., 2003) or real data (Mumby et al., 1997; Holden and LeDrew, 1999; Andréfouët et al., in press; Call et al., 2003; Capolsini et al., in press) show that Landsat (TM or ETM+), SPOT HRV or ASTER can differentiate 3 to 6 subtidal habitat types (e.g. coral reef, seagrass, sand, hard substrate) with reasonable overall accuracy (60–75%). A compilation of results suggests a predictive character to the relationship overall accuracy (Y) vs. number of classes (X) with $Y = -3.90X + 86.38$ ($r^2 = 0.63$) for Landsat ETM+, and $Y = -2.78X + 91.69$ for Ikonos ($r^2 = 0.82$) (Andréfouët et al., in press).

Image data acquired from airborne platforms typically have spatial resolutions of 1–3 m, with analog aerial photographs achieving resolutions <1 m. Such data provide smaller area coverage than that acquired from satellites, thus requiring multiple overlapping flight lines to generate maps of comparable spatial extent. On the other hand, the higher spatial resolution of airborne imagery enables finer habitat discrimination (see Fig. 1). As virtually all such discriminations are spectral-based, the coupling of imaging spectroscopy with airborne platforms provides a powerful tool for benthic habitat

Table 1
Status of remote sensing coral reefs

Platform	Boat		Aircraft			Satellite				
Sensor type	Acoustic	Laser	Laser	Hyperspectral	Photographic film	Hyperspectral	Multispsectral (high resol.)	Multispectral (med resol.)	Radiometer	Multispectral (low resol.)
Example of sensor	RoxAnn	FILLS	Lidar, LADS	AVIRIS, CASI, ATM	SLR camera	Hyperion	Ikonos, Quickbird	Landsat TM, SPOT, IRS	AVHRR, ATSR, GOES	SeaWiFS, MODIS, OCM
Coral species										
Coral & algal cover		?	?	? ✓		?				
Reef community (>5 classes)	? ✓	?	? ✓	✓	✓	?	? ✓			
Occurrence of bleaching		?	?	?	? ✓	?	?			
Structural complexity (rugosity)	✓		?	?	?		?			
Reef geomorphology	✓		✓	✓	✓	?	✓	✓		
Location of shallow reefal areas	✓		✓	✓	✓	?	✓	✓	?	? ✓
Reef community (<5 classes)	✓	✓	✓	✓	✓	?	✓	✓		
Bathymetry	✓		✓	✓	? ✓	?	✓	✓		? ✓
Coastal land use (& change)			✓	✓	✓	✓	✓	✓	✓	

✓ indicates routinely possible; ? ✓ indicates demonstrated in limited cases only; ? indicates untested but we believe it to be possible; blank indicates not possible (at this time).
LADS = Laser Airborne Depth Sounder, AVIRIS = Airborne Visible/Infrared Imaging Spectrometer, CASI = Compact Airborne Spectrographic Imager, ATM = Airborne Thematic Mapper, SLR = Single Lens Reflex, TM = Thematic Mapper, SPOT = Systeme Probatoire de l'Observations de la Terre, IRS = Indian Remote Sensing Satellite, AVHRR = Advanced Very High Resolution Radiometer, GOES = Geostationary Operational Environmental Satellite, SeaWiFS = Sea Wide Field-of-view Sensor, MODIS = Moderate Resolution Imaging Spectroradiometer, OCM = Ocean Colour Monitoring.

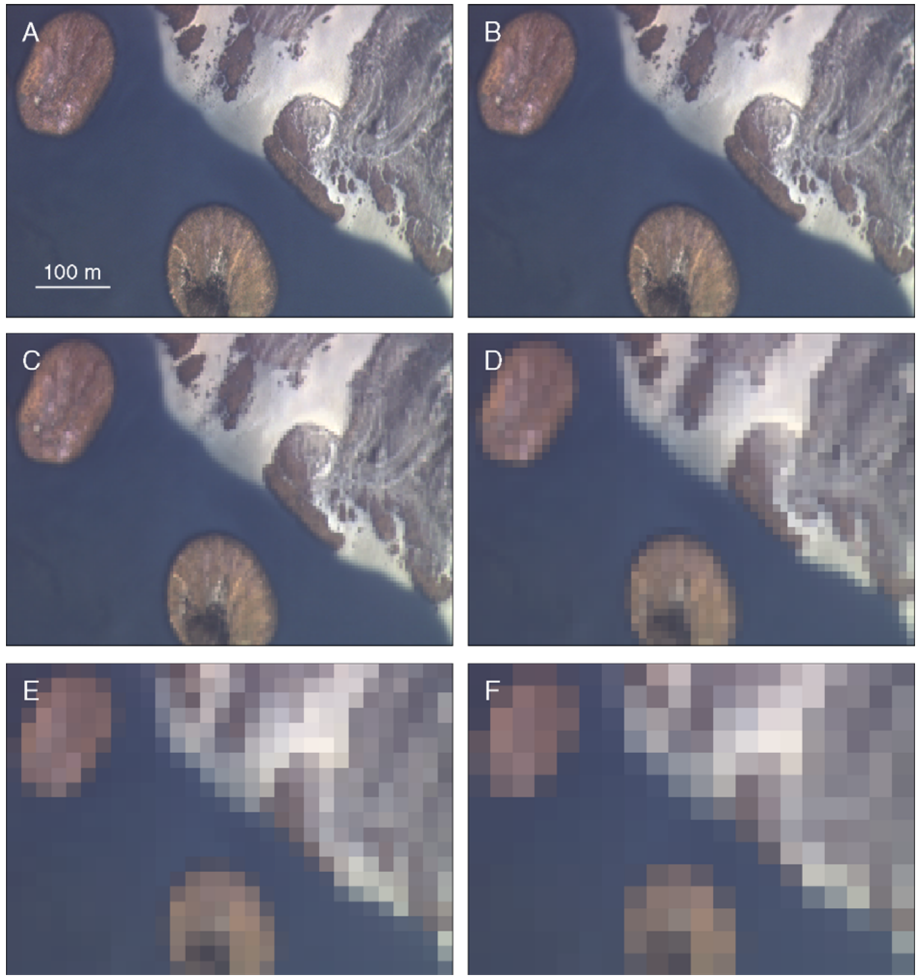

Fig. 1. Backreef and lagoonal environment of Kaneohe Bay, Oahu, Hawaii at simulated pixel resolutions common to multi and hyperspectral remote sensing systems. A: 1 m (aerial imaging). B: 2 m (aerial imaging, Quickbird). C: 4 m (aerial imaging, Ikonos). D: 10 m (several proposed spaceborne). E: 20 m (AVIRIS, SPOT). F: 30 m (Landsat).

mapping. For example, in the Turks and Caicos Islands, CASI over-flights discriminated nine specific benthic species assemblages with an overall accuracy of 81% (Mumby et al., 1998). It appears that spectral resolution (the number and width of spectral bands) is more important than spatial resolution for discriminating between reef communities (Mumby et al., 1997; Hochberg and Atkinson, 2003), and several well-placed, narrow ($\sim$10 nm) spectral bands are necessary to detect subtle differences in reflectance between some reef communities (e.g. seagrass vs. algal beds, coral vs. algae, brown algae vs. green algae, Hochberg et al., 2003). Some current satellite sensors have spatial resolutions commensurate with airborne imagery (e.g. Ikonos and Quickbird at 4 and 2.5 m, respectively), but these have only 1–3 broad (50–100 nm) water-penetrating bands. Despite these spectral limitations, these sensors perform well for the overall mapping of a reef (Mumby and Edwards, 2002; Andréfouët et al., in press), but cannot be used to target specific habitats of interest with very high accuracy.

A relatively new and unexplored technology for mapping reefs involves laser technology. Chlorophyll, when irradiated with green, blue or UV light emits red light (fluoresces). Non-photosynthetic pigments also exhibit fluorescence features (Mazel et al., 2003). Using these properties, active sensing using laser-induced fluorescence can be used to map ocean chlorophyll (Yoder et al., 2001), bathymetry, and offers promise for subtidal benthic habitat mapping (Hardy et al., 1992). Coral, macroalgae and seagrass can all be differentiated based on their fluorescence spectra (Myers et al., 1999; see review by Hedley and Mumby, 2002). An experimental ship-borne towed laser (FILLS) was been deployed by Mazel et al. (2003) in the Bahamas and Florida. The sensor was deployed at night to avoid complicating factors of solar radiation, and clearly identified fluorescent biota on the seabed. Cniderians were grouped together and therefore the cover of scleractinian corals could not be estimated accurately. However, whilst these sensors are not available for commercial use, they show promise for future development.

Although many satellite sensors have inadequate spectral information to detect a shift in reef community structure, a time series of images, sometimes using different sensors, may identify areas which have undergone change. For example, Landsat TM images, which date back to the early-mid 1980s, were used to identify empirically changes in the albedo of reefs in Florida, which were caused by increases in macroalgal cover after the mass mortality of the urchin *Diadema antillarum* (Dustan et al., 2001). Time-series of TM and ETM+ images were also processed semi-analytically to observe coral loss (Palandro et al., 2003). Palandro et al. (in press) combined IKONOS and aerial photographs to estimate the variation in coral cover in the Florida Keys. Interimagery studies, when based on aerial photographs, may allow changes to be assessed over several decades (Lewis, 2002). Research in change detection methods is now being directed in one empirical and two analytical avenues. First, using temporal differences in the spatial homogeneity or heterogeneity (i.e. texture) of the benthic assemblages (LeDrew et al., 2000); second, intercalibration and correction of multisensor time-series; and third, sensitivity analysis of change detection methods using images acquired in quick succession, where it is assumed that real changes have not yet occurred (Andréfouët et al., 2001b).

Interest is growing in using remote sensing to monitor reef health. Perhaps the most dramatic phenomenon to affect reefs is mass coral bleaching which can render more than 99% of coral colonies white in a matter of days (Hoegh-Guldberg, 1999). In situ studies of coral spectra reveal that severely bleached and non-bleached corals differ in their colour or "spectral signature" (Holden and LeDrew, 1998, 2001b). Several studies have modelled the feasibility of detecting a bleaching event using remote sensing (Yamano et al., 2002) but a detailed empirical study on the Great Barrier Reef found that very small pixels (0.1–0.8 m) are required to quantify accurately the percentage of bleached corals (Andréfouët et al., 2002a). Such small pixel sizes are unlikely to be practical for most mapping applications and are beyond the availability of current satellite sensors. Larger pixels may be appropriate for reefs with wide monospecific, coral-dominated areas but this is likely to be the exception rather than the rule. The most likely solution to this limitation of pixel size is the application of methods which estimate the cover of substrata *within* pixels. These methods, known as spectral unmixing, were developed for terrestrial remote sensing, where there is no interfering water column. Adaptations of spectral unmixing methods to aquatic environments are only beginning to appear (Hedley and Mumby, 2003).

Few studies have attempted to map the health or status of reefs directly. A study in French Polynesia used a high resolution airborne multispectral sensor to classify individual pixels as either live *Porites*, recently-dead *Porites* (within last 6 months after a bleaching event), old-dead *Porites*, dead *Pocillopora*, *Halimeda* and *Hydrolithon onkodes* (Mumby et al., 2001a; Mumby et al., in press). Although reef-scale estimates of coral cover were of a similar accuracy and precision to field survey, attempts to map coral cover must be repeated under a variety of physical and biological conditions to guage the applicability of this result to other reefs.

Remote sensing is not just used for measuring the status of reefs. A number of studies are continuing to investigate the scientific and management applications of detailed reef mapping. For example, Roelfsema et al. (2002) have used Landsat TM imagery to investigate the spatial distribution of microalgae on reefs. Andréfouët and Payri (2001) have made large-scale assessments of reef productivity in French Polynesia by using SPOT images to scale-up field measurements of production and calcification in individual lagoonal habitats. Mumby (2001) has developed methods that explicitly link the species composition of individual communities to maps of community distribution. Such methods identify hotspots of beta and habitat diversity and aid spatial decision-making.

1.2. What environmental properties of reefs can we measure using remote sensing (Table 2)?

A fundamental environmental parameter for coral reefs is sea surface temperature (SST). Although the National Oceanic and Atmospheric Administration (NOAA) have been routinely measuring SST since the mid 1970s, the techniques and sensors did not evolve sufficiently until the mid 1980s. As a result, we now have accurate daily SST measurements since 1985, and post processing techniques such as those employed by the Advanced Very High Resolution Pathfinder SST project, have provided consistent global SST data for the period 1985 to present (Kilpatrick et al., 2001). Beginning experimentally as early as 1997, the National Oceanic and Atmospheric Administration (NOAA) has taken advantage of this long data series by developing a SST climatology upon which they have based a number of satellite global 50-km resolution experimental products (initially SST Bleaching "HotSpot" anomalies and then Degree Heating Week (DHW) products) as indices of coral bleaching related thermal stress. The coral bleaching HotSpot is not a typical climatological SST anomaly. It is a measure of the occurrence of the hottest SST for a region and as such is an anomaly that is not based on the average of all SST, but on the climatological mean temperature of the climatologically hottest month (i.e. the maximum of the monthly mean SST

Table 2
Physical parameters which can be measured using remote sensing

Platform	Aircraft		Satellite								
Sensor type	Hyper-spectral	Micro-wave	Hyper-spectral	Multi-spectral (high resol.)	Multi-spectral (medium resol.)	Meteoro-logical	Multispectral (low resol.)	Radar scattero-meter	Radar	Radar Altimeter	Radiometer
Examples of sensor	AVIRIS, CASI, ATM,	SLFMR	Hyperion	IKONOS, Quickbird	Landsat TM, SPOT, IRS	GOES, GMS, ME-TEORSAT	SeaWiFS, MODIS	SAR Quick-SCAT	TRMM	TOPEX, Jason-1	AVHRR, ATSR
Sea surface temperature						✓	✓ (MODIS)				✓
Ultraviolet radiation						✓					✓
Photosynthetically active radiation			✓	✓		✓	✓				✓
Light attenuation coefficients	✓		✓	✓	✓		✓				✓
Cloud cover			✓	✓	✓	✓	✓				✓
Ocean sea level										✓	
Salinity		✓									
Chlorophyll-a concentration	✓		✓	✓	✓		✓				
Algal blooms	✓		✓		✓		✓				
Suspended sediment concentration	✓		✓	✓	✓		✓				✓
Wind speed								✓		✓	
Ocean circulation						✓	✓			✓	✓
Coastal circulation (feature tracking)						✓	✓				? ✓
Precipitation									✓		

✓ indicates routinely possible; ? ✓ indicates demonstrated in limited cases only; ? indicates untested but we believe it to be possible; blank indicates not possible (at this time).
AVIRIS = Airborne Visible/Infrared Imaging Spectrometer, CASI = Compact Airborne Spectrographic Imager, ATM = Airborne Thematic Mapper, SLFMR = Scanning Low Frequency Microwave Radiometer, TM = Thematic Mapper, SPOT = Systeme Probatoire de l'Observations de la Terre, IRS = Indian Remote Sensing Satellite, GOES = Geostationary Operational Environmental Satellite, GMS = Geostationary Meteorological Satellite, METEORSAT = Meteorological Satellite, SeaWiFS = Sea Wide Field-of-view Sensor, MODIS = Moderate Resolution Imaging Spectroradiometer, ERS-1 = European Remote Sensing Satellite, QuikSCAT = Quik Scatterometer, TRMM = tropical rainfall mapping mission, TOPEX (/Poseidon) = The Ocean Topography Experiment, AVHRR = Advanced Very High Resolution Radiometer, ATSR = Along-Track Scanning Radiometer and Advanced Along-Track Scanning Radiometer.

climatology, often referred to as the MMM climatology). This climatology, derived from the Polar-orbiting Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR) SSTs for the period 1985–1993, is static in time but varies in space (Strong et al., 1997) (Table 2).

HotSpot values provide a measure of the intensity of the thermal stress, but do not measure the cumulative effects of that thermal stress on a biological system such as coral reefs. In order to monitor this cumulative effect, a thermal stress index, called a Degree Heating Week (DHW), was developed. DHW represents the accumulation of HotSpots for a given location, over a rolling 12-week time period (see Fig. 2). Preliminary indications show that a HotSpot value of less than one degree is insufficient to cause visible stress on corals. Consequently, only HotSpot values $\geqslant 1$ °C are accumulated (i.e. if we have consecutive HotSpot values of 1.0, 2.0, 0.8 and 1.2, the DHW value will be 4.2 because 0.8 is less than one and therefore does not get used). One DHW is equivalent to one week of HotSpot levels staying at 1 °C or half a week of HotSpot levels at 2 °C, and so forth. These products have been successful in monitoring several major coral bleaching episodes around the globe (Goreau et al., 2000; Wellington et al., 2001; Liu et al., 2003). Both HotSpot and DHW charts are produced by NOAA Coral Reef Watch twice weekly in near-real time from composite nighttime AVHRR SST products. These products, along with descriptions of the methodologies, are Web-accessible at: orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html.

Solar radiation underpins primary production on coral reefs and contributes to the phenomenon of coral bleaching (Hoegh-Guldberg, 1999). Geostationary satellites are the best platforms from which to monitor solar radiation (including measurements of Photo synthetically Active Radiation, PAR) since they can provide measurements of reflected solar radiation at hourly intervals throughout a day, whereas Polar orbiting satellites are only capable of one measurement per day at best. This high temporal resolution is necessary because of the high temporal variability of cloud during a day. There are a number of geostationary satellites which are currently capable of providing useful solar radiation products: e.g. GOES East and West, GMS and Meto-Sat. The Australian Bureau of Meteorology has had an operational solar radiation product based on GMS for a number of years (www.bom.gov.au/nmoc/archives/Solar/). Currently this is a land based product, however it is likely to be extended off shore soon. NOAA have a similar experimental product for GOES, which includes both land and sea (orbit-net.nesdis.noaa. gov/arad/fpdt/goescat_v4/html/GOES_VI_10_a_radianes.html). This product is expected to be operational in the near future.

Ultraviolet radiation (UV-B 280–320 nm and UV-A 321 to about 400 nm) and high levels of photosynthetically active radiation (PAR, 400–760 nm) can have a variety of negative impacts on marine phytoplankton, zooplankton, neuston, nekton and benthos (Hardy and Gucinski, 1989). The proportion of UV-B radiation that reaches the Earth is increasing due to stratospheric ozone depletion. To understand the role of UV radiation in the marine environment, accurate measurements of incident solar UV over season, latitude and depth in the water column are needed. Satellites provide global time series measurements of incident ultraviolet radiation. The Total Ozone Mapping Spectrometer (NASA, 2002) measures the reflected spectrum from the Earth to estimate total column ozone thickness. Data products from this satellite also include maps of erythemal (biologically damaging) UV reaching the Earth's surface. NASA also sponsors two Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) instruments as part of a program with the Naval Research Laboratory. One is SUSIM ATLAS aboard the Space Shuttle and the other, SUSIM UARS, aboard the Upper Atmosphere Research Satellite. Both measure the absolute irradiance of solar ultraviolet in the wavelength range 115–410 nm (NRL, 2002). A Canadian Satellite, MAESTRO (Environment Canada, 2002), will measure the intensity of visible and UV sunlight passing through a vertical profile (slice) of the Earth's atmosphere as the sun rises and sets and will provide information on atmospheric attenuation.

Since the all of these UV specialist satellites are polar orbiters, it is necessary to combine their measurements

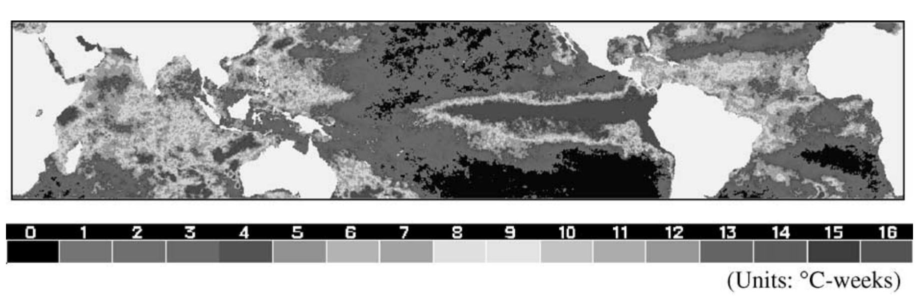

Fig. 2. Degree Heating Weeks (DHW) product accumulated for the year of 1998. This is a measure of accumulated heat stress experienced by corals during 1998 (www.osdpd.noaa.gov/PSB/EPS/SST/dhw_retro.html).

of ozone and UV with the visible measurements made by geostationary satellites to obtain accurate daily UV estimates.

Any satellites capable of deriving solar radiation measurements can be and often are used to derive various cloud products. In the past, the AVHRR has been used to derive cloud cover and cloud types. However, due to the high temporal variability of cloud and the relatively low temporal coverage of AVHRR overpasses, most cloud based studies have used geostationary satellites to derive their cloud products (Schmidt et al., 2001; Schmertz et al., 2002). Large-scale estimates of cloud cover can be acquired from the International Satellite Cloud Climatology Project (ISCCP) derived from AVHRR data (isccp.giss.nasa.gov/). The spatial resolution of the products ranges between 30 and 280 km. The temporal resolution ranges from 3 h to monthly and yearly mean climatologies. However, not all years have been processed to date. The current climatology does not yet integrate yet the time-frame 1999–2003.

In summary, satellites provide global synoptic maps of solar radiation (including UV and PAR) reaching the ocean surface. These data, together with water column attenuation coefficients, can provide an estimate of solar radiation quantities received by marine organisms.

The wavelength-dependent, optical property, diffuse light attenuation coefficient (k) describes the clarity of water and is influenced by pigments, dissolved organic material and suspended sediment concentrations. Instantaneous estimates of k can be calculated on reef waters for almost any spectral band that penetrates water. A common method is to identify patches of similar bottom type (e.g. sand) across a range of depths and plot the natural log of reflectance against depth (k is the slope, see (Maritorena, 1996)). In addition to variations caused by rivers or estuarine input, there is evidence that optical properties of the water depend on the bottom type (Boss and Zaneveld, 2003), though the practical implications in terms of remote sensing algorithms are not clear since the magnitude of the changes are small. Vertically, recent studies of the surface and bottom spectral reflectance (Holden and LeDrew, 2001a, 2002) and the entire profile of k (Newman and LeDrew, 2001) have illustrated some difficulties with the assumption of a k that is constant with depth, particularly over highly reflective surfaces (e.g. sand, and then associated resuspension and scattering). This fact is predicted by the dependence of k on the directional structure of the ambient light field, which is strongly affected by the reflecting surfaces at the sea surface and sea floor (Mobley, 1994). It is also important to note that "k" as measured by a passive remote sensor is an operational term that incorporates water column-integrated diffuse attenuation of both the upward and downward light flows, while in situ "k" is measured for a single direction at a time, up or down and the two are not equal (Mobley, 1994).

At meso-scales, changes in the water quality beyond reefs are detected daily using observations from ocean colour sensors (CZCS, SeaWIFS, MODIS, MERIS). Observations from such sensors may be used to track water masses and aid understanding of the connectivity patterns within a coral reef province, even for short-term events such as hurricanes (Andréfouët et al., 2002b). However, ocean colour instruments were not designed to work in Case-II (turbid) waters or in shallow coastal regions where reflectance from the seabed complicates the calculation of factors that control ocean colour, namely, chlorophyll, sediments, and colour dissolved organic matter (IOCCG, 2000). Thus, the water quality above reefs cannot be monitored directly using remote sensing. Recent work has attempted to use anomalies in SeaWiFS-derived water leaving radiances as an indirect monitoring method. Using this approach, anomalies subsequent to algal bloom developments were detected and tentatively related to local benthos mortalities (Hu et al., 2003). Further research is needed into the use of ocean colour anomalies for detected changes in either the water column or benthos.

Wind speed and direction has for some time been a much sort-after meteorological parameter. Hourly images of clouds have been used for some time to derive cloud drift wind products for various levels within the atmosphere (e.g. Le Marshall et al., 1997). The advent of microwave scatterometers (e.g. ERS 1 and 2, Envisat and Quickscatt) allowed meteorologists to improve their indirect measurements of the speed and direction of surface marine winds (Draper and Long, 2002). The main limitation of these methods for coral reefs, is that the algorithms assume a fully developed sea in deep water (unfortunately these assumptions rarely hold around most coral reefs).

The same satellites and sensors that are used to derive wind parameters are also used to derive wave products. These products include significant wave height and length. Unfortunately, for use with coral reefs, they suffer from the same assumption of a fully developed sea. The NOAA's National Center for Environmental Prediction (NCEP) produce a blended satellite/model wave product which can be found at (www.pmel.noaa.gov/bering/pages/env_wave.html).

Rainfall is a much under-utilised remote sensing product in coral reef research and management. Salinity is one of the major stressors of corals and rainfall is key to understanding the stress induced by low salinity levels due to the presence of fresh water, either from river outflows to direct input to the reef system via tropical storms. There are two main techniques for deriving rainfall from space, one is based on the use of thermal infrared measurements of cloud top temperatures whereas the other is based on microwave attenuation by the rain itself. Ebert and Manton (1998) give an intercomparison for some of these techniques when used on various satellites, both polar orbiting and geostationary. The Tropical Rainfall Measuring Mission (TRMM) is a recent example of a sensor package specifically designed for the measurement of rainfall; (www.eorc.nasda.go.jp/TRMM/index_e.htm and trmm.gsfc.nasa.gov/).

2. Conclusions

One of the most pressing issues affecting reef health is mass coral bleaching. Mass bleaching results from an interaction between elevated sea temperature and either PAR, UVB or both (Brown, 1997; Hoegh-Guldberg, 1999; Mumby et al., 2001b). Although SST, UV and PAR can be extracted from satellite data, no studies have yet combined such data with thermal and radiative transfer models to predict the risk of bleaching conditions at the reef surface. Indeed, there is much scope to improve the forecasting of mass bleaching by integrating the products of a suite of satellite sensors.

Remotely-sensed data are becoming progressively more diverse and useful. As time goes on, climatological time series data derived from remote sensing products become ever more meaningful and better able to distinguish acute disturbance from typical fluctuations in the marine environment. Perhaps the greatest obstacles to the use of such data are cost and access. Future high resolution satellite instruments will hopefully provide the kinds of data which must currently be acquired from an aircraft at great cost. It is hoped that developments in internet technology will improve data dissemination of a diverse, but complementary, suite of products. Finally, we stress the need to expand training opportunities so that a wider community of practitioners can choose how to select and interpret the most appropriate information for a given application.

Acknowledgements

This paper was made possible by the World Bank/GEF Targeted Research Strategy on Coral Reefs. We thank Andy Hooten and Marea Hatziolos for giving us the opportunity to form a working group and put our heads together.

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