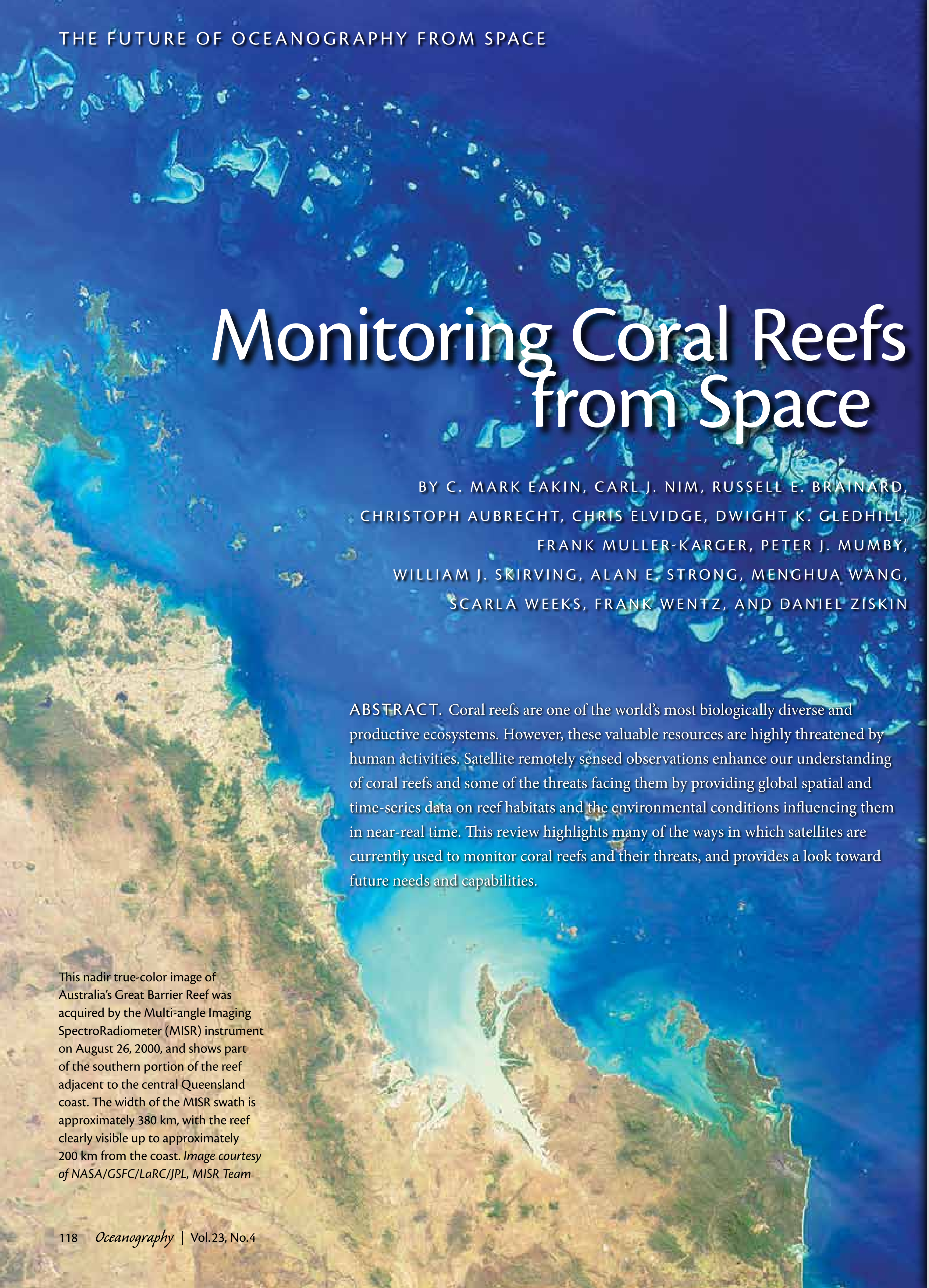

Monitoring Coral Reefs from Space

BY C. MARK EAKIN, CARL J. NIM, RUSSELL E. BRAINARD,
CHRISTOPH AUBRECHT, CHRIS ELVIDGE, DWIGHT K. GLEDHILL,
FRANK MULLER-KARGER, PETER J. MUMBY,
WILLIAM J. SKIRVING, ALAN E. STRONG, MENGHUA WANG,
SCARLA WEEKS, FRANK WENTZ, AND DANIEL ZISKIN

ABSTRACT. Coral reefs are one of the world's most biologically diverse and productive ecosystems. However, these valuable resources are highly threatened by human activities. Satellite remotely sensed observations enhance our understanding of coral reefs and some of the threats facing them by providing global spatial and time-series data on reef habitats and the environmental conditions influencing them in near-real time. This review highlights many of the ways in which satellites are currently used to monitor coral reefs and their threats, and provides a look toward future needs and capabilities.

This nadir true-color image of Australia's Great Barrier Reef was acquired by the Multi-angle Imaging SpectroRadiometer (MISR) instrument on August 26, 2000, and shows part of the southern portion of the reef adjacent to the central Queensland coast. The width of the MISR swath is approximately 380 km, with the reef clearly visible up to approximately 200 km from the coast. *Image courtesy of NASA/GSFC/LaRC/JPL, MISR Team*

INTRODUCTION

Coral reefs are one of the world's most biologically diverse and productive ecosystems (Porter and Tougas, 2001). They provide abundant ecological goods and services (Moberg and Folke, 1999) and are central to the socio-economic and cultural welfare of coastal and island communities throughout tropical and subtropical oceans by contributing at least $30 billion (US$) to the global economy when combined with tourism and recreation, shoreline protection, fisheries, and biodiversity services (UNEP-WCMC, 2006). Unfortunately, a range of human activities adversely impacts these valuable resources. Among the key threats are improper fishing activities, land-based sources of pollution, climate change, ocean acidification, and habitat destruction (Dodge et al., 2008; NOAA Coral Reef Conservation Program, 2009).

Satellites have the capacity to enhance our understanding of coral reef threats by obtaining global information on environmental conditions in near-real time and by providing spatial and time-series data relevant to management that are not practically obtained by in situ observations alone. This paper highlights the various ways remote-sensing data are being used to map and monitor coral reefs. It explains some remote-sensing tools commonly used to measure coral reef parameters of interest, how this information aids coral reef managers, some of the limitations of current technologies, and research gaps. Table 1 summarizes the coral reef parameters that we can currently measure by satellites. Mumby et al. (2004) and Andréfouët (in press) provide additional reviews of satellite uses, methods, and applications for coral reefs, including discussions about using remote sensing to monitor key physical parameters that influence the conditions of coral reefs.

MONITORING CORAL REEF ENVIRONMENTAL CONDITIONS

Coral reefs are exposed to a number of stressors from their surroundings. Although most satellites were not designed to observe coral reefs, many remote-sensing instruments provide valuable environmental data that are relevant to reef conditions. Calibration and validation data have been used to strengthen these data in shallow, near-shore environments, allowing coral reef managers and researchers to use this information to both understand the role of stressors and to better manage coral reef resources.

Physical Parameters

With the growing consequences of global climate change, there is greater need for monitoring impacts in coral reef areas. Increasing anthropogenic concentrations of atmospheric CO_2 have numerous direct and indirect deleterious impacts on coral reefs. Carbon dioxide imparts an important control on the radiative heat balance of Earth's atmosphere, resulting in warming of both the atmosphere and the ocean (IPCC, 2007). Rising upper ocean temperatures, as indicated by sea surface temperature (SST), have increased the frequency and intensity of widespread thermal stress events that can cause mass coral bleaching (Eakin et al., in press), and this bleaching is expected to continue into the future (Hoegh-Guldberg et al., 2007, 2008). Rising SST can also result in an increase in infectious disease outbreaks

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C. Mark Eakin *(mark.eakin@noaa.gov) is Coordinator, National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch, Silver Spring, MD, USA.* **Carl J. Nim** *is NOAA Knauss Fellow, Coral Reef Watch, Silver Spring, MD, USA.* **Russell E. Brainard** *is Supervisory Oceanographer, NOAA Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division, Honolulu, HI, USA.* **Christoph Aubrecht** *is Research Scientist, Austrian Institute of Technology, Vienna, Austria.* **Chris Elvidge** *is Physical Scientist, NOAA National Environmental Satellite, Data, and Information Service (NESDIS), National Geophysical Data Center, Earth Observations Group, Boulder, CO, USA.* **Dwight K. Gledhill** *is Associate, NOAA Office of Oceanic and Atmospheric Research (OAR), Atlantic Oceanographic and Meteorological Laboratory, Silver Spring, MD, USA.* **Frank Muller-Karger** *is Professor, University of South Florida, Institute for Marine Remote Sensing, St. Petersburg, FL, USA.* **Peter J. Mumby** *is Professor, University of Queensland, School of Biological Sciences, Brisbane St. Lucia, Queensland, Australia.* **William J. Skirving** *is Contractor, NOAA Coral Reef Watch, Kirwan, Queensland, Australia.* **Alan E. Strong** *is Contractor, NOAA Coral Reef Watch, Silver Spring, MD, USA.* **Menghua Wang** *is Oceanographer, NOAA NESDIS Center for Satellite Applications and Research, Camp Springs, MD, USA.* **Scarla Weeks** *is Research Scientist, University of Queensland, Centre for Spatial Environmental Research, Brisbane St. Lucia, Queensland, Australia.* **Frank Wentz** *is Research Scientist and Proprietor, Remote Sensing Systems, Santa Rosa, CA, USA.* **Daniel Ziskin** *is Research Scientist, University of Colorado, Cooperative Institute for Research in Environmental Science, Boulder, CO, USA.*

Table 1. Remote sensing platforms and sensors relevant to the monitoring of coral reefs and associated habitats. *Adapted from Mumby et al. (2004) and the Directory of Remote Sensing Applications for Coral Reef Management by the Remote Sensing Working Group of the Global Environment Facility Coral Reef Targeted Research & Capacity Building for Management Program*

Symbology: ✓ indicates well-established, ?✓ indicates fairly well-established, ? indicates experimental, ✓* indicates data should be used in conjunction with acoustic sonar devices, blank indicates not currently possible.

PLATFORM		**SHIP**	**AIRCRAFT**		**SATELLITE**			
SENSOR TYPE		Acoustic	Imaging Spectrometers (Hyperspectral)	Laser	Microwave	Multispectral (High Spatial Resolution)	Hyperspectral (Medium Spatial Resolution)	Multispectral (Medium Spatial Resolution)
EXAMPLE(S) OF PLATFORM OR SENSOR		RoxAnn, BioSonics	AVIRIS, CASI, ATM, HyMap	lidar, LADS	Aquarius, SMOS	IKONOS, QuickBird	EO-1 Hyperion	Landsat MSS/TM/ETM, SPOT, IRS
APPLICATION	Reef location		✓	✓		✓	✓	✓
	Mangroves		✓			✓	✓	✓
	Sea grass beds		✓			✓	✓	✓
	Reef geomorphology/habitats		✓	✓		✓	✓	✓
	Reef community type		✓	✓		✓*		
	Beta (between habitat) diversity		✓			✓*		
	Connectivity of fish between mangroves and coral reefs							?
	Coral cover (live vs. dead)		?					
	Reef structural complexity (rugosity)	?		?✓				
	Coral bleaching events		?			?		
	Bathymetry	✓		✓		✓		✓
	Coral sensitivity to thermal stress							
	Wave exposure							
	Coral bleaching thermal stress							
	Coral disease risk							
	Physical model inversion methods		?			?		
	Sea surface temperature							
	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							

Table continued on next page...

Acronyms: AVIRIS = Airborne Visible/Infrared Imaging Spectrometer, CASI = Compact Airborne Spectrographic Imager, ATM = Airborne Thematic Mapper, HyMap = Hyperspectral Mapper, lidar = light detection and ranging, LADS = Laser Airborne Depth Sounder, SLFMR = Scanning Low Frequency Microwave Radiometer, SMOS = Soil Moisture and Ocean Salinity, MSS = Multispectral Scanner, TM = Thematic Mapper, ETM = Enhanced Thematic Mapper, SPOT = Satellite Probatoire de l'Observations de la Terre, IRS = Indian Remote Sensing Satellite

Table 1, continued. Remote sensing platforms and sensors relevant to the monitoring of coral reefs and associated habitats. *Adapted from Mumby et al. (2004) and the Directory of Remote Sensing Applications for Coral Reef Management by the Remote Sensing Working Group of the Global Environment Facility Coral Reef Targeted Research & Capacity Building for Management Program*

Symbology: ✓ indicates well-established, ?✓ indicates fairly well-established, ? indicates experimental,
✓* indicates data should be used in conjunction with acoustic sonar devices, blank indicates not currently possible.

PLATFORM		**SATELLITE**					
SENSOR TYPE		Multispectral (Low Spatial Resolution)	Meteoro-logical	Radar Scatterometer	Synthetic Aperture Radar	Radar Altimeter	Radiometer
EXAMPLE(S) OF PLATFORM OR SENSOR		SeaWiFS, MODIS, Envisat MERIS	GOES, GMS, Meteosat	ASCAT	ASAR	Jason-1/2	POES, TRMM, AVHRR, ATSR
APPLICATION	Reef location	✓					
	Mangroves	✓					
	Sea grass beds	✓					
	Reef geomorphology/habitats						
	Reef community type						
	Beta (between habitat) diversity						
	Connectivity of fish between mangroves and coral reefs						
	Coral cover (live vs. dead)						
	Reef structural complexity (rugosity)						
	Coral bleaching events						
	Bathymetry						
	Coral sensitivity to thermal stress		?				?
	Wave exposure			?	?		?
	Coral bleaching thermal stress						✓
	Coral disease risk						?
	Physical model inversion methods						
	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				✓		

Acronyms: SeaWiFS = Sea-viewing Wide Field-of-view Sensor, MODIS = Moderate Resolution Imaging Spectroradiometer, Envisat MERIS = Environmental Satellite - Medium Resolution Imaging Spectrometer, GOES = Geostationary Operational Environmental Satellite, GMS = Geosynchronous Meteorological Satellite, Meteosat = Meteorological Satellite, ASCAT = Advanced Scatterometer, ASAR = Advanced Synthetic Aperture Radar, POES = Polar Operational Environmental Satellite, TRMM = Tropical Rainfall Measuring Mission, AVHRR = Advanced Very High Resolution Radiometer, ATSR = Along Track Scanning Radiometer

(Bruno et al., 2007). The following section explains how satellite observations are used to monitor a variety of climate-related physical parameters, such as SST, solar radiation, and wind.

Thermal Stress and Coral Bleaching

Polar-orbiting environmental satellites (POES) provide near-real time observations and have measured SST at 4-km spatial resolution since 1981. The US National Oceanic and Atmospheric Administration's (NOAA's) Coral Reef Watch (CRW) provides a suite of operational global satellite coral bleaching monitoring products at 0.5° latitude-longitude spatial resolution, produced twice weekly (Liu et al., 2006) from nighttime SSTs (Figure 1a). Over 20 years of NOAA SST data have been reprocessed to produce a consistent data set at 4-km spatial resolution (Kilpatrick et al., 2001). Analysis of the 22-year Pathfinder data set suggests that the water temperatures of most coral reef areas have been increasing at 0.2–0.4°C per decade (Strong et al., 2009). This warming agrees with studies that indicate corals may need to acclimate their thermal tolerance by 0.2–1.0°C per decade to survive repeated coral bleaching events predicted under future climate scenarios (Donner et al., 2005).

The CRW coral bleaching HotSpot, released in 1996 (Strong et al., 1997) and made operational in 2002 (Liu et al., 2003), was the first coral-specific product developed by NOAA's National Environmental Satellite, Data, and Information Service (NESDIS). Based on the "ocean hot spots" concept introduced by Goreau and Hayes (1994), HotSpots are positive temperature anomalies that exceed the maximum monthly mean (MMM) SST climatology for each 0.5° pixel, thereby identifying currently thermally stressed regions. These HotSpots are accumulated over a moving 12-week window to produce CRW's Degree Heating Week (DHW) index that is highly predictive of bleaching occurrence and severity. Significant coral bleaching is expected to occur one to three weeks after reefs begin

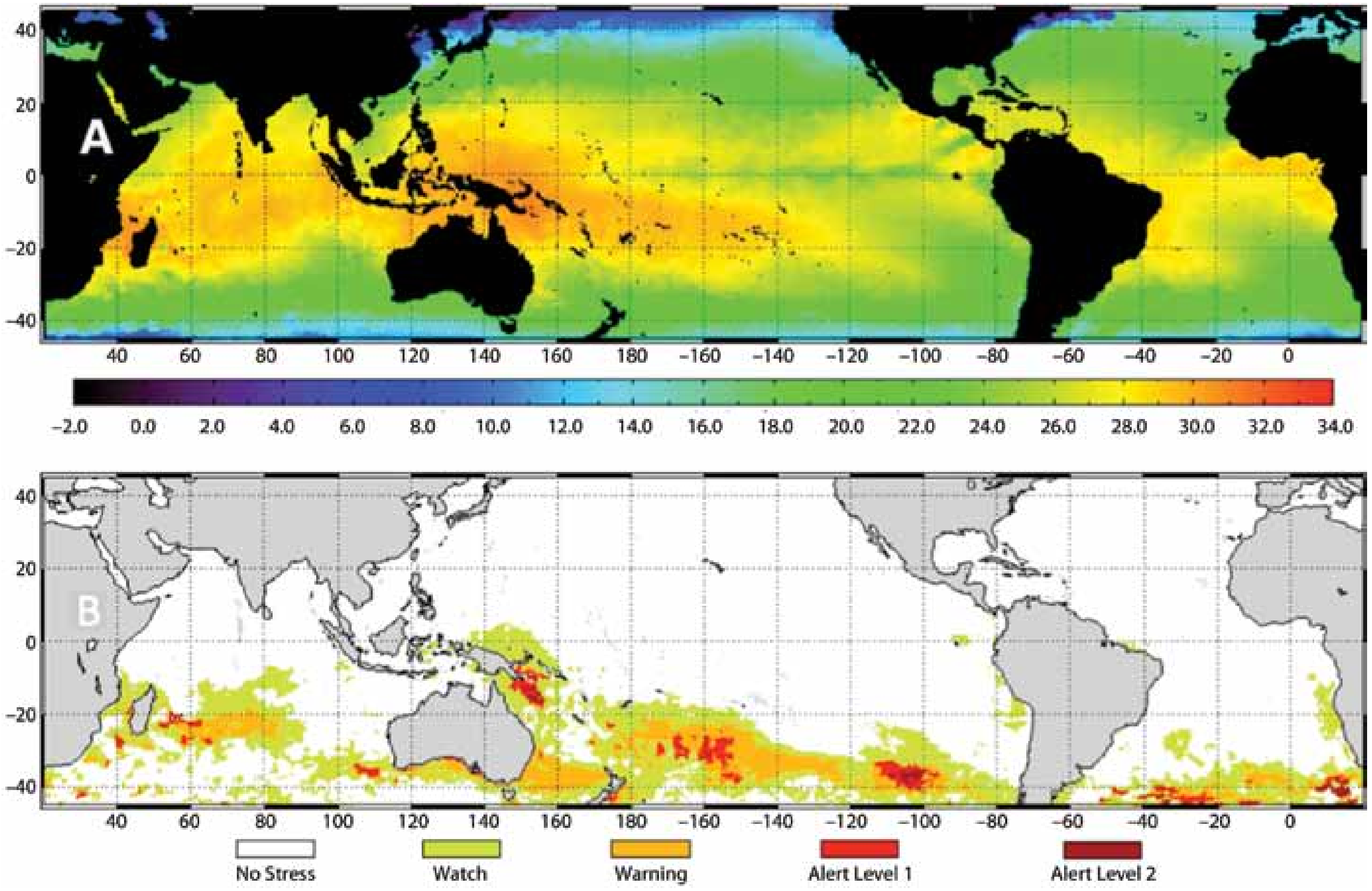

Figure 1. NOAA Coral Reef Watch near-real time satellite global 50-km nighttime product suite for February 9, 2009: (A) sea surface temperatures (SST), (B) coral bleaching alert area product that combines HotSpot and Degree Heating Week products.

to experience DHW values ≥ 4°C-weeks, and mass bleaching and the onset of coral mortality is expected after DHW values ≥ 8°C-weeks. CRW later combined the HotSpot and DHW data to produce the Coral Bleaching Alert Area product (Figure 1b)—a singular product, of particular value to managers, that displays areas where bleaching thermal stress currently is expected. In the future, HotSpot and DHW algorithms at 1–4 km resolutions from NOAA and National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensors (Hu et al., 2009) will be used to evaluate relationships between SST high-resolution spatial structure and coral reef ecosystem responses (Inia Soto, University of South Florida, *pers. comm.*, September 27, 2010).

CRW's "Virtual Stations" also provide time series SST data for over 190 selected reef sites around the world that can be used by coastal resource managers for predicting coral bleaching. Though based on satellite data, Virtual Stations are somewhat analogous to having broad-scale sensors of the surface waters surrounding a reef. CRW uses Virtual Stations to provide automated bleaching alert e-mails that notify subscribers when coral reefs are experiencing conditions conducive to bleaching. These bleaching alerts provide opportunities for local reef managers and researchers to visually assess coral conditions and take management actions if local conditions warrant them.

The spatial resolution of these data and the variability of oceanographic conditions in these areas require calibration and validation of remote-sensing data to improve analyses. Many SST products are calibrated using offshore, rather than nearshore, SST observations (Emery et al., 2001). SST data, especially new high-resolution products, need to be verified for use in coral reef environments. Van Hooidonk and Huber (2009) used a meteorological forecast verification method to quantitatively assess the quality of the derived DHW product. Field observations of corals have also been used to verify predicted bleaching events and determine if large-scale high temperatures or local stressors were the cause (McClanahan et al., 2007). Detailed comparisons of satellite remote sensing to actual community changes will permit the development of models with strong management application, such as bleaching susceptibility models for identifying resilient reef areas (Maina et al., 2008).

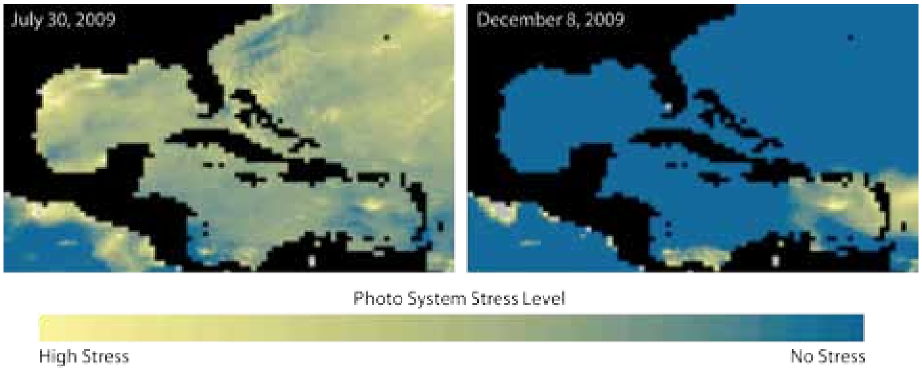

Figure 2. Prototype of the new NOAA Light Stress Damage product combining thermal and light stress as a bleaching predictor.

Solar Radiation and Coral Bleaching

A variety of projects over the past decade have examined the use of geostationary satellite data to study aspects of solar radiation over coral reefs (Tovar and Baldasano, 2001; Hansen et al., 2002; Kandirmaz et al., 2004). In 2009, NOAA developed a suite of experimental surface solar radiation products based on data from Geostationary Operational Environmental Satellite (GOES) systems that were calibrated and validated to provide insolation estimates over oceanic waters (http://www.osdpd.noaa.gov/ml/land/gsip). These products measure total daily global ocean surface insolation. These data have allowed CRW and its partners to develop a new set of coral bleaching products that endeavour to provide a combined measure of satellite-derived thermal stress and light as an index of stress on coral photosystems. Figure 2 shows a mock-up of the product that CRW is developing.

Bleaching Weather: The Influence of Wind

Local weather patterns shape the potential for coral bleaching. In particular, wind influences local bleaching patterns by affecting temperature, light, water-column mixing, and sediments. As wind speeds decrease, turbulent vertical mixing and evaporative cooling are reduced, sensible heat loss increases, and the likelihood of anomalously high temperatures and light penetration increases (Skirving and Guinotte, 2001; Obura, 2005). Additionally, low winds increase water-column stratification, increase light penetration by enhancing sediment settlement, and facilitate photo-degradation of colored dissolved

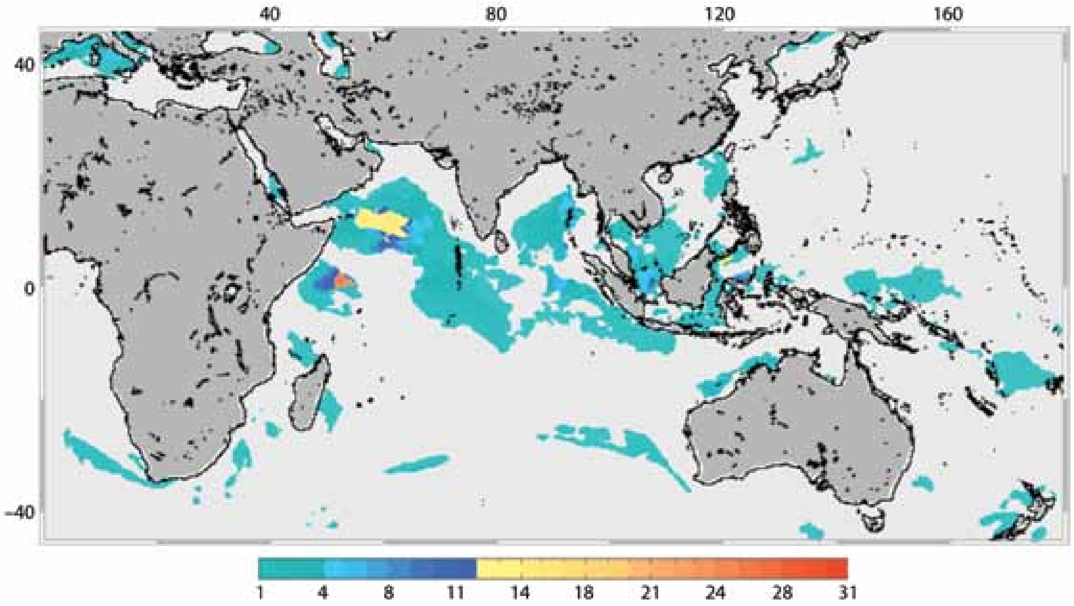

Figure 3. NOAA/NESDIS Coral Reef Watch near-real-time satellite 25-km Doldrums experimental product for April 22, 2007, in the Indian Ocean region. The color scale indicates the number of days over which the daily mean National Climatic Data Center Blended Sea Winds remained below 3 m s^{-1}.

organic material (Manzello et al., 2006). CRW has developed an experimental Doldrums product using NOAA's National Climatic Data Center (NCDC) Blended Sea Winds Product (Zhang et al., 2006). The experimental Doldrums product identifies regions of mean wind speed below 3 m s^{-1} and records the persistence (days) of such conditions (Figure 3; CRW 2007; http://coralreef-watch.noaa.gov/satellite/doldrums).

Analyses of long-term patterns of winds may provide additional insights into conditions around coral reefs. A recent analysis of satellite Special Sensor Microwave Imager (SSM/I) observations suggests that precipitation and total atmospheric water have increased equally at a rate of ~ 1% per decade over the past two decades (Wentz et al., 2007). A least-squares linear fit of SSM/I wind speed for each 2.5° grid cell was calculated after removing the seasonal variability to provide a decadal trend map of wind speed (Figure 4) and compared with wind trends from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) from ship-based observations. Winds averaged from 30°S to 30°N increased by 0.04 m s^{-1} (0.6% per decade), resulting in wet areas becoming wetter (Wentz et al., 2007). Wentz et al. (2007) suggest that two decades may be too short for extrapolating these short-term trends into longer ones; however, continuation of these trends could significantly impact circulation, mixing, and temperature regulation of waters around reefs in the Indo-West Pacific, the heart of coral biodiversity and abundance.

Chemical Parameters

Though corals predominantly occur in clear, oligotrophic waters, nutrient-rich runoff from land-based sources of pollution (LBSP) often results in algal overgrowth of corals and coral recruits (Adey, 2000). Phosphate pollution can inhibit calcium carbonate ($CaCO_3$) deposition, slowing coral growth (Muller-Parker and D'Elia, 1997). Increased nutrients from LBSP influence trophic interactions on coral reefs, including phytoplankton blooms that may smother corals (Guzmán et al., 1990) or enhance recruitment of larval *Acanthaster planci* (crown-of-thorns sea stars) that feed on corals (Brodie, 2005). Suspended sedimentation causes coral reef degradation (Rogers, 1990; Field et al., 2008) by damaging and smothering corals, thus restricting their growth (Fabricius, 2005). Sediment plumes and phytoplankton blooms are recognizable by satellite ocean color sensors. Unfortunately, various factors, including coastal aerosols, mixed signals from the water column, and heterogeneous benthic substrates, make quantitative monitoring of ocean color parameters a challenge in coral reef environments (IOCCG, 2000).

Land-Based Sources of Pollution

Many coral reefs are naturally exposed to the influence of nutrients and sediment from both large and small rivers (Muller-Karger and Castro, 1994; Soto et al., 2009) and from nonpoint runoff. LBSP are of growing concern as land and coastal zones are developed. LBSP include a wide variety of materials that individually or collectively threaten coral reefs' health. Of primary need for monitoring the coral reef environment are remotely sensed observations of rainfall events and their associated runoff, which often lead to reduced salinity, increased turbidity and sedimentation, and observations of transported nutrients that contribute to phytoplankton blooms.

Remote sensing of coastal water-quality parameters (e.g., suspended sediment and chlorophyll *a*) using visible radiance is difficult with ocean color sensors due to their technical design, but advances in remote-sensing science have provided some innovative solutions (Muller-Karger et al., 2005). Many global, open-water ocean color products derived from moderate spatial resolution satellite ocean color sensors (e.g., SeaWiFS [Sea-viewing Wide Field-of-view Sensor, MODIS) employ atmospheric correction algorithms that use the near-infrared (NIR) bands (Gordon and Wang, 1994; IOCCG, 2010). The complexity of turbid, coastal areas prompted researchers to develop a shortwave infrared (SWIR) atmospheric correction algorithm (Wang, 2007) to improve the accuracy of ocean color products in these waters (Wang et al., 2009). One avenue of recent work has enhanced preprocessing techniques to derive coastal coral reef water-quality parameters by combining deep-water algorithms (Lee et al., 2002; Qin et al., 2007) with shallow-water mapping schemes. Although ocean color advances have been made for deriving coastal water-quality parameters in coral reef ecosystems (Wang et al., 2009), many challenges remain.

Ocean Acidification

As human activities continue to increase carbon dioxide in the atmosphere ($CO_{2,atm}$), much of this CO_2 is absorbed into surface ocean waters. Surface ocean CO_2 ($CO_{2,aq}$) then reacts with water to form carbonic acid, thereby lowering pH; hence, the term "ocean acidification" (Caldeira and Wickett, 2003). This process also consumes carbonate ions, reducing the degree of saturation (Ω_{sp}) of seawater with respect to calcium carbonate. This may result in reduced coral growth rates and compromise the structural integrity of coral reefs (Manzello et al., 2008; Veron, 2008; Gledhill et al., 2009). Many experimental studies have suggested a relationship between declining seawater saturation and the rate at which many marine organisms (including many coral species) produce calcium carbonate, albeit the relationship can prove complex when interactions with temperature and nutrients are considered (for a review see Doney et al., 2009). Monitoring ocean acidification, particularly secular declines in Ω_{arg} in response to rising

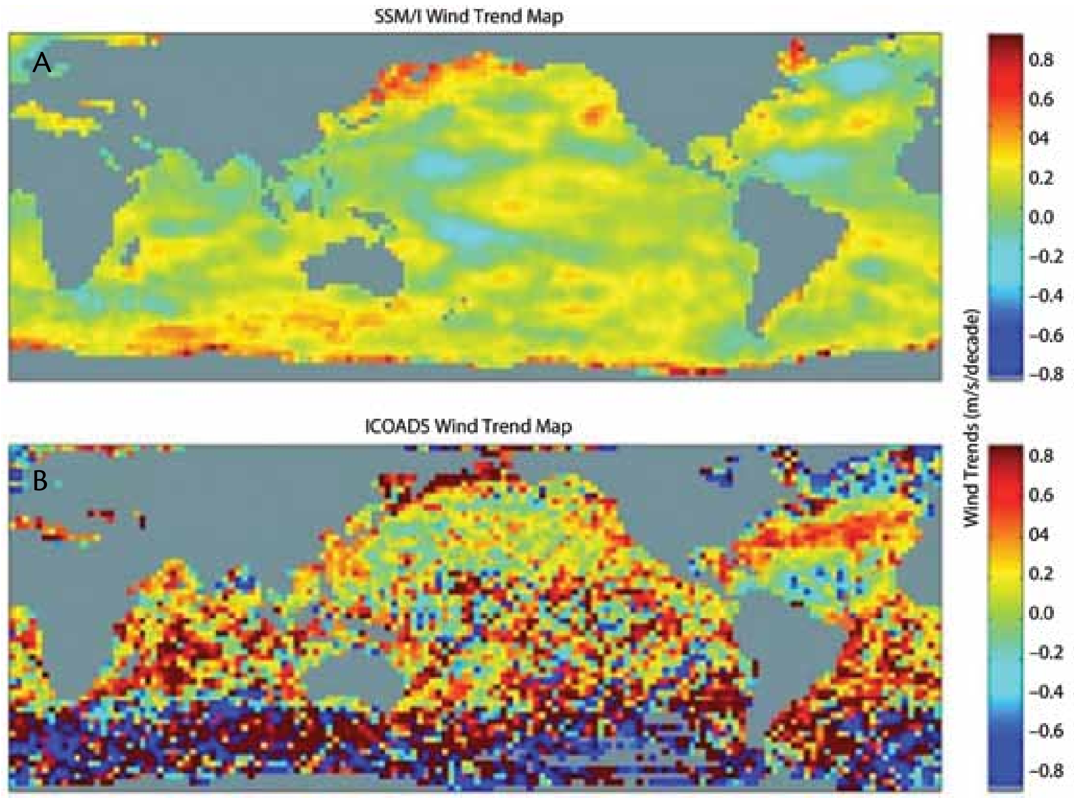

Figure 4. Surface-wind trends for the period July 1987 through August 2006 computed at a spatial resolution of 2.5°. (A) Special Sensor Microwave Imager (SSM/I) satellite wind trends. (B) International Comprehensive Ocean-Atmosphere Data Set (ICOADS) ship wind trends. In the North Pacific and North Atlantic where ICOADS ship observations are more abundant, the two data sets show similar trends. *From Wentz et al. (2007)*

atmospheric $CO_{2,atm}$, could yield insights into the expected regional responses of coral reef ecosystems.

In situ measurements of ocean chemistry provide the most accurate means of tracking ocean acidification, but such measurements are inherently limited in space (repeat sampling, moored stations) and/or time (ship surveys). Although current satellites cannot directly measure changes in ocean carbonate chemistry, they can provide synoptic observations of a range of physical and optical parameters that allow us to model these changes. In 2008, CRW and NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) developed and released an experimental Ocean Acidification Product Suite (OAPS) (http://coralreefwatch.noaa.gov/satellite/oa). The product provides a monthly 0.25° x 0.25° analysis of modeled sea surface carbonate chemistry (Ω_{arg}, $pCO_{2(sw)}$, total alkalinity, carbonate ion, and bicarbonate ion) within the oceanic waters of the Greater Caribbean Region (Gledhill et al., 2008), based on a set of regionally specific algorithms, satellite remote-sensing data, and shipboard in situ observations.

The OAPS algorithms merge multiple environmental data sets, including $CO_{2,atm}$ concentrations, sea-level air pressure, temperature, and relative humidity. The dominant controls on surface Ω_{arg} dynamics within these oligotrophic waters are $pCO_{2(sw)}$ availability, SST, and salinity. Typically, SST imparts the greatest subannual control on CO_2 uptake within these oligotrophic waters, for which OAPS uses the currently available 0.25° daily NOAA optimal interpolated (OI) SST product, which depends upon remotely sensed radiometric SST data from in situ, Advanced Very High Resolution Radiometer (AVHRR), and Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) sensors (Reynolds et al., 2007). While it is hoped that salinity dependency will be partially met through the application of Aquarius satellite sea surface salinity data sets in coming years, the current model relies upon HYbrid Coordinate Ocean Model (HYCOM) + Navy Coupled Ocean Data Assimilation (NCODA) 1/12° Analysis GLBa0.08 salinity fields. Given the coarse spatial and temporal resolution of Aquarius, it is likely that even future OAPS iterations will retain some dependence on HYCOM-produced salinity fields.

By solving for both surface alkalinity and $pCO_{2,sw}$ it is possible to fully describe the carbonic acid system (that is, solve the distribution of the various carbonate species), permitting OAPS to solve for Ω_{arg}. More-sophisticated algorithms are currently under development that would provide for a more general application of OAPS to other tropical regions through the addition of other variables (e.g., winds, chlorophyll *a*).

Salinity

Sea surface salinity directly influences seawater density and chemical processes such as carbonate chemistry. Until recently, salinity was measured in situ or by airborne microwave radiometers to assess the role of riverine plumes on seagrass and coral reefs (Klemas, 2009). With the launch of the European Soil Moisture and Ocean Salinity (SMOS) satellite in 2009, and NASA's Aquarius satellite in 2010, monthly global averages of sea surface salinity now can be remotely measured with an accuracy of 0.1 and 0.2 psu at 200-km and 150-km spatial resolution, respectively (Robinson, 2004; Martin, 2004; Lagerloef et al., 2008). As mentioned above, salinity at this resolution may be helpful in driving models to provide downscaled salinity to improve our monitoring of alkalinity and, thus, ocean carbon chemistry. It may also help provide information on increased runoff from large rivers as well as production of warm hypersaline waters over extensive shallow banks.

Coastal Development

Although current satellites cannot identify complex chemical pollutants, it is possible to use satellite observations of human activity to provide a proxy for these other stressors. Understanding the extent of urbanization and human activity can provide a proxy for localized impacts such as pollutants, runoff, fishing, and recreational use of reefs. A prominent indicator of human occupation visible from space is artificial night lighting. Observable features have included biomass burning, massive offshore fisheries, and infrastructure lights. NOAA has processed nighttime lights data acquired by the US Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) (Aubrecht et al., 2008) in order to integrate the brightness and distance of lights near known coral reef sites as a proxy for human development stresses. Light proximity index (LPI) values have been calculated for the three stressors observable in nighttime lights: human infrastructure, gas flares, and heavily lit fishing boats. The algorithm computes the contribution of lights declining with increased distance from reefs. LPI since 1992 shows increased human settlements near coral reefs

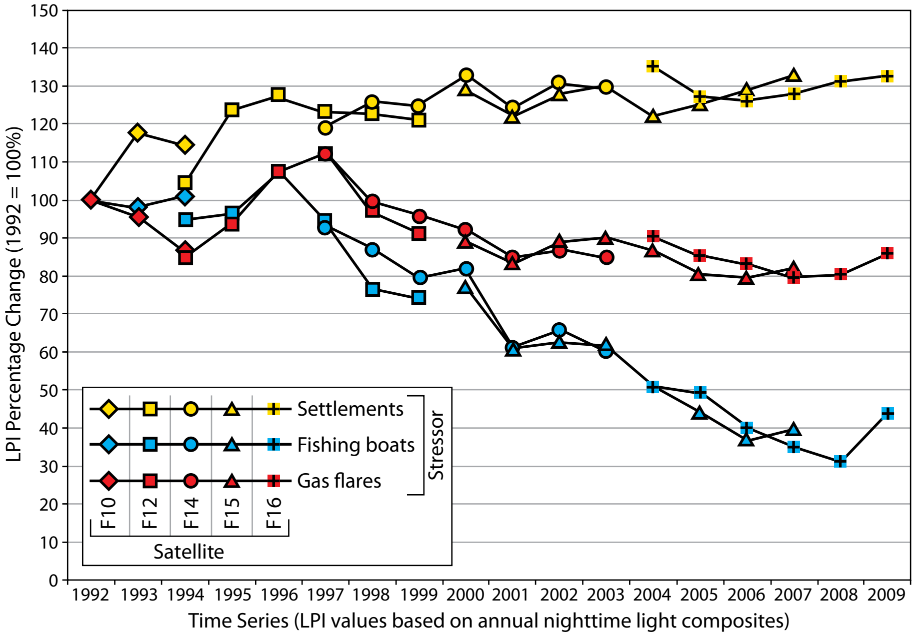

Figure 5. Light proximity index (LPI) percent change over time (1992–2009) from human settlements, lit fishing boats, and offshore gas flares for the reefs of the world. LPI values are normalized by absolute number of reef points to show percent change over time. Colors correspond with stressors and point shapes with the satellite used.

(Figure 5), a reflection of the expanding populations and infrastructural development seen in coastal areas in many parts of the world. In contrast, lit fishing boats activity has declined and gas flares near reefs show a more complex pattern with dips in 1994 and 2001, and a peak in 1997. LPI can provide a valuable tool for coastal management, especially in areas where other data on coastal development may be limited.

MANAGEMENT APPLICATIONS

Measurement of environmental parameters is helpful to coral reef managers because it alerts them of conditions when coral reefs in their jurisdictions are in need of direct monitoring or management action. There are times, however, when in situ data are not sufficient for monitoring, or reef locations are too remote to gather in situ data. In these cases, high-resolution remote-sensing data can provide researchers and resource managers with needed data. The availability of high-resolution satellite data has increased in recent years due to launching of more advanced sensors, application of emerging technologies in sensor designs, and new algorithms. These data are used to study reef carbonate dynamics (Moses et al., 2009), bathymetry in coral reef areas (Hogrefe et al., 2008), geomorphology and biodiversity of coral reefs (Andréfouët and Guzman, 2005; Knudby et al., 2007), and coral reef fish species richness, communities, and fisheries (Mellin et al., 2009; Hamel and Andréfouët, 2010). They also allowed managers to more effectively integrate in situ and remotely sensed data (Scopélitis et al., 2010). Given the breadth of literature on this topic, this section will only provide a survey of some important applications, including marine protected area (MPA) management, habitat characterization, and some important biological parameters of coral reefs.

The Use of Remote Sensing for Marine Protected Areas

Analyses of coral reefs using high-spatial-resolution (30-m pixel size or less) data span a broad scale of applications, including MPA design and evaluation (Green et al., 2009; Dalleau et al., 2010), study of ecosystem associations, (e.g., coral reefs with seagrass beds and mangroves), and investigations of the ecology of coral reefs and the organisms that live in them (e.g., fish). Although the bulk of these projects are conducted at local scales, there are calls to automate these techniques for use at broader scales (Andréfouët, 2008). NOAA's analysis of MPA characteristics and design in the northwestern Hawaiian Islands and in Puerto Rico has used remotely sensed data in conjunction with in situ measurements of coral habitat and spectral reflectance characteristics to produce benthic habitat maps for shallow-water coral reefs. These baseline habitat maps provide resource managers and researchers with essential information for planning MPAs, monitoring changes, and evaluating MPA effectiveness in both the Pacific (Friedlander et al., 2007, 2008) and the Caribbean (García-Sais et al., 2008).

Habitat Characterization

Mapping has proven to be a valuable tool for understanding the interconnections between coral reefs and associated habitats, such as the role mangroves play as juvenile reef fish nurseries (Mumby, 2006). Such ecosystem-based perspectives can aid the designation and management of MPAs.

High-spatial-resolution mapping of mangrove and seagrass species has been explored (Myint et al., 2008; Phinn et al., 2008) and regional seagrass mapping using Landsat data has been assessed for broader applications across the Caribbean (Wabnitz et al., 2008).

A wide variety of remote-sensing platforms and algorithms are available for habitat mapping. A diverse literature exists on habitat mapping using satellite sensors such as Satellite Pour l'Observation de la Terre (SPOT) and Landsat Thematic Mapper (TM) at a spatial resolution of tens of meters (LeDrew et al., 2000), and on using high-spatial-resolution sensors such as the commercial Earth-observation satellites IKONOS and QuickBird (Mumby and Edwards, 2002; Andréfouët et al., 2003; Mishra et al., 2006). Even greater accuracies can be obtained by including data from airborne sensors like the Compact Airborne Spectrographic Imager (CASI) either as the prime data source (Mumby et al., 1998; Bertels et al., 2008) or in combination with satellite data (Rowlands et al., 2008).

> “SATELLITE TECHNOLOGIES HAVE BECOME ESSENTIAL TOOLS FOR MONITORING CORAL REEF HEALTH AND THE INCREASING THREATS CORAL REEFS FACE AROUND THE GLOBE.”

Perhaps the most ambitious project to characterize the habitats of coral reefs worldwide was the Millennium Coral Reef Mapping Project (MCRMP) (Andréfouët et al., 2002), which used Landsat data to identify geomorphological characteristics of coral reefs on a global scale. Data obtained in this effort have already informed numerous studies on strategic MPA placement, reef condition assessments (Burke and Maidens, 2004), and both climate forcing of reef growth on the Great Barrier Reef and climate change influences on biogeochemical budgets in French Polynesian atolls (Andréfouët et al., 2006).

Seafloor bathymetry and benthic rugosity are important variables to coral reef researchers and managers alike. Pseudo-bathymetry has been derived from IKONOS data in a number of studies (Lyzenga et al., 2006), modified by applying nonlinear inversion models (Su et al., 2008), and used to fill the gap between terrestrial digital elevation models (DEMs) and sonar-acquired bathymetry (Hogrefe et al., 2008). In other studies using light detection and ranging (lidar), rugosity maps were developed to illustrate massive stony coral colonies on patch reefs (Brock et al., 2006) and to investigate statistical relationships between rugosity and reef fish communities (Kuffner et al., 2007). Other studies combined bathymetry with habitat maps derived from remote-sensing satellites to drive models that predict coral reef fish distribution (Pittman et al., 2007; Knudby et al., 2008; Knudby et al., 2010). Mellin et al. (2009) advocated a “hierarchy of habitat” for predicting coral reef fish habitats using geomorphology, benthic assemblages, rugosity, and depth as key habitat variables.

Biological Parameters of Coral Reef Ecosystems

Coral reef cover is a parameter of great interest to researchers and managers. To date, there have been three approaches to quantifying changes in the benthic composition of coral reefs using coral and macroalgae cover as key indictors of reef health. A number of scientists have used time-series data to detect changes in overall reflectance that can be attributed to major changes in benthic state. For example, Dustan et al. (2001) analyzed a Landsat time series from Florida and found a change in “temporal texture” associated with the die-off of long-spined sea urchins. These indirect methods are useful, but the data have been difficult to interpret because multiple changes in benthic characteristics may have similar effects. A second approach uses high-resolution optical data to measure changes in reef spectra. Researchers either interpret these data directly (Lesser and Mobley, 2007) or extract characteristic spectral derivatives from them (Holden and LeDrew, 1998) to classify live and recently dead coral (Mumby et al., 2004, 2001). For these studies, it is important that the reefs have a clear-water environment and are devoid of brown macroalgae, which are frequently spectrally confused with coral (Hedley and Mumby, 2002). The wider efficacy of these methods for evaluating coral cover is still under investigation (Hedley et al., 2004; Joyce et al., 2004).

Figure 6. Image differencing, or spectral brightening, of Nikunau Island, Kiribati. The difference image (far right) shows a gold color where presumably bleaching has occurred.

A third approach to mapping corals has used sonar to discriminate branching corals, such as *Acropora* spp., from other reef structures (Purkis et al., 2006).

Mass coral bleaching has been successfully detected using remotely sensed observations in cases where the extent of bleaching is pronounced in high-coral-cover reef habitats; Figure 6). High spatial resolution is key to reliable remote detection of coral bleaching (Andréfouët et al., 2002). Elvidge et al. (2004) developed a method for detecting the brightening of reef areas when corals bleach using pairs of high-resolution multispectral images. The technique involves detection of spectral brightening observed when comparing satellite images acquired before the bleaching event with images collected during the bleaching event. This technique has continued to be refined and applied to multiple satellite sensors (Daniel Ziskin, University of Colorado at Boulder, *pers. comm.*, September 27, 2010). However, images like those in Figure 7 only provide a general index of reef bleaching and cannot separate bleaching of corals from bleaching of crustose coralline algae in reef systems, limiting their value for reefs where the community structure is poorly known. Additionally, as long as these approaches require the purchase of costly satellite imagery, they will only be practical for remote areas that cannot be reached by divers.

THE FUTURE OF MONITORING CORAL REEFS FROM SPACE

Improvements in three major areas are increasing the potential for using remotely sensed data to monitor coral reefs: resolution, spectral bands, and algorithms. Whether it is remote sensing of stressors, environmental parameters, or habitats and their changes, increased spatial and temporal resolution provide new ways that coral reefs can be monitored. Unfortunately, there is often a trade-off between spatial and temporal resolutions, as finer-resolution imagery is frequently obtained through narrower swaths and a corresponding increase in time between repeated observations. However, improved technology, such as off-nadir viewing, and image processing are helping to resolve this issue. Higher-resolution applications also require a larger data set of in situ observations for calibrating and validating changes, especially in highly variable nearshore environments.

At the same time, a greater portion of the electromagnetic spectrum is being used in remote sensing. Enhanced optical systems, such as multispectral to hyperspectral sensors covering more of the visible and nearby bands, will be used to detect changes in benthic habitats and will do a better job of separating benthic features from water-column properties. Because coral reefs normally exist in shallow, clear waters, many optical bands can “see” the bottom. This attribute is good for habitat measurements, but it creates problems for separating changes in the benthos from changes in the water column. Both enhanced spatial and spectral resolution are essential to resolving these problems and will provide the quantitative data needed to answer many resource-monitoring challenges that currently exist for coral reef ecosystems.

None of these improvements are sufficient, however, without considerable work to develop, calibrate, and validate new and improved algorithms. Because satellites can only measure a small set of parameters directly, most of what we monitor from satellites is the result of complex algorithms that derive the parameters of interest. This is also where the combination of multiple instruments and spectral bands show great promise in enhancing our

A CLASSROOM ACTIVITY USING SATELLITE SEA SURFACE TEMPERATURES TO PREDICT CORAL BLEACHING

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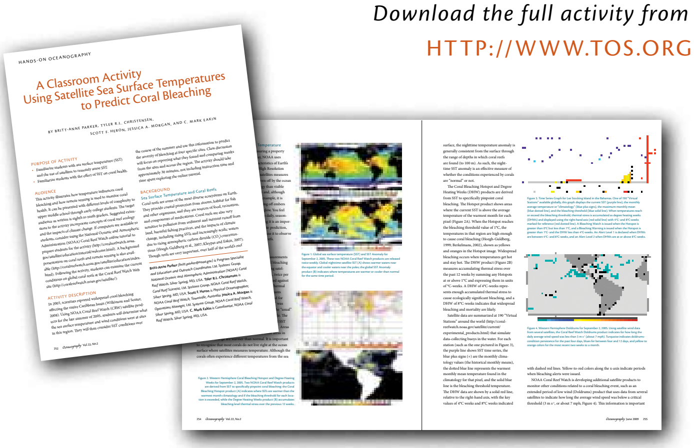

HANDS-ON OCEANOGRAPHY

A Classroom Activity Using Satellite Sea Surface Temperatures to Predict Coral Bleaching

BY BRITT-ANNE PARKER, TYLER R.L. CHRISTENSEN, SCOTT F. HERON, JESSICA A. MORGAN, AND C. MARK EAKIN

remote-sensing capabilities.

Although satellite remote sensing is already an essential tool for assisting global efforts to map and monitor coral reefs, as described above, many opportunities and challenges remain. Will future technological advances enable us to monitor the abundance and distribution of coral reef fish, near-real-time changes in benthic habitats, indices of coral reef biodiversity, or other indicators of ecosystem health and ecological responses to climate change and ocean acidification? Where else do we need to stretch the envelope of remote-sensing capabilities to best address these challenges? Resource managers are asking when scientists will provide tools to alert them when changes occur in the cover of seagrass on the ocean bottom. They would like to see hypoxic or "black water" events that kill fish. These managers would also like to know when changes in water quality cause harmful algal blooms or the spread of bacterial mats across the seafloor. They would like to know when diseases are spreading through ecosystems. Some of these capabilities are likely to be available over time scales of a few years while others will likely take decades and require significant advances in the development of new sensors and algorithms.

Some of these needs will be answered by advancing the use of remotely sensed and in situ data to initiate and support numerical models. These models estimate environmental parameters (as was done for ocean acidification) or impacts, such as changes in community composition. In many cases, these models integrate multiple data sets to provide new estimates of unmeasured parameters. These estimates may serve as solutions to scientific questions that inform management needs or may be a bridge until new sensors are available. The development and launch of new satellite sensors is a slow process, and agencies involved need to better incorporate the needs of resource managers into their instrument and satellite development processes. At the same time, we need to identify key parameters that must be collected with high quality and continuously to understand long-term changes to coral reefs and the water quality and oceanographic conditions influencing them.

Coral reefs are important and valuable ecosystems. Satellite technologies have become essential tools for monitoring coral reef health and the increasing threats coral reefs face around the globe. We need to continue to advance the tools available and the science behind them in order to make these tools as useful as possible. As the anthropogenic threats to coral reefs continue to mount, we need to continue our diligent use of all tools at our disposal to keep these valuable resources healthy.

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