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INTRODUCTION

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Remote sensing: a key tool for interdisciplinary assessment of coral reef processes

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Introduction

Growing consensus exists among scientists that global climate change really is upon us and is taking an increasingly heavy toll on coral reefs. The scientific literature and conference proceedings abound with reports about impacts. But how bad is the situation really? Are we being misled by small-scale studies that justifiably ring the alarm bell for a specific area without necessarily having relevance for the world at large? Clearly, the immense challenge of understanding the severity and patterns of impacts on coral reefs due to globally changing climate patterns requires tools that allow coherent and speedy investigation of large areas—ranging in size from reef systems to entire ocean basins. Fortunately, over recent decades, remote sensing has developed into an increasingly refined and widely used tool that has found many applications within the coral reef research community. It is with this in mind that the present special issue was conceived.

At first glance, the papers published in this special "Remote Sensing and Coral Reefs" issue of Coral Reefs may look like a disparate collection of studies, spanning most coral reef regions worldwide (Pacific, Caribbean, Red Sea, Indian Ocean) using a variety of sensors (SeaWiFS, Landsat, IKONOS, LIDAR, in situ spectrometry), methods (analytical, statistical, empirical, modeling), scales (regional to species-level), and applications related to various reef processes. However, each of these 15 studies is representative of one of the current axes that characterizes the integration of the remote sensing (RS) tool in coral reef science and management.

Under the broad label "coral reef," we accepted submissions for this special issue targeting any subject ranging from individual coral colonies to the largest reef systems (Great Barrier Reef) or carbonate banks (Bahamas). We also expected studies on deeper coral reefs and carpets using acoustic technology but none of the letters of interest were followed by an actual submission, suggesting that more efforts are required to interpret acoustic data in a reef context. The growing body of investigators considering in-water active sensors for deep or shallow surveys beyond the limit of optical remote sensing will certainly justify another compilation of state-of-the art works in the future.

We explicitly encouraged submission of papers presenting the integration of remote sensing data into studies addressing reef mega-processes (sensu Hatcher 1997), beyond just methodological development. Eventually, only seven studies revealed new environmental knowledge using relatively standard remote sensing data or practices (Acker et al. 2004; Berkelmans et al. 2004; Hochberg et al. 2004; Otis et al. 2004; Penland et al. 2004; Andréfouët et al. 2004; Naseer et al. 2004). Conversely, eight papers can be primarily qualified as "methodological" since they investigate the potential of new high spatial resolution sensors (Elvidge et al. 2004; Brock et al. 2004), new ways to combine remote sensing and in situ data (Purkis and Pasterkamp 2004; Joyce et al. 2004), and modeling (Ouillon et al. 2004; Wooldridge and Done 2004), and investigate the behavior of spectral measurements of reef benthos as prelude to hyperspectral surveys (Hedley et al. 2004; Karpouzli et al. 2004). Of course, most of these method papers also provide some environmental information, but this is clearly not the primary goal. The environmental knowledge was known beforehand and used to critically

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assess the results (e.g. the coral bleaching studies by Elvidge et al 2004; Wooldridge and Done 2004). Nevertheless, all papers are innovative and reveal the methodological axis where reef scientists and remote sensing practitioners are collaboratively devising better tools. The balance between methodological and applied papers proves that remote sensing of coral reefs still has much room to grow. This is not because of a lack of interest or poor potential, but because new capacities constantly emerge and need to be tested. On the other hand, the applied papers show that part of the ''older'' technology has been already transferred into the hands of reef scientists working in the more traditional disciplines of biology or geology who use remote sensing strictly as a tool and not a research direction in itself. This transfer took roughly 20 years.

The use of remote observations acquired on coral reefs by buoys, ships, underwater vehicles, planes, balloons, kites, and satellites is not new. Aerial photographs or sonar surveys have provided information on physical and biological reef structures for several decades (e.g. Great Barrier Reef, Hopley 1978, 1982). Today, historical aerial photographs provide the only way to assess reef evolution over several decades quantitatively (Lewis 2002). As such, we can only regret that systematic collection of aerial photographs didn't occur in the early decades of the last century to provide an objective reference point. Nevertheless, remote sensing has suffered from the early eighties to late nineties as the ''tool without applications'' syndrome especially for space-borne observations that were generally judged to be too coarse in spatial resolution. In short, the pioneers promised a lot but didn't deliver what was expected by reef scientists.

New requirements for science and management, and recent evolution of remote sensing technology data collection and processing capabilities, have been of such a scale, that any modern study aimed at understanding, comparing, and monitoring coral reef processes in time and space without the integration of some sort of remote sensing data, is likely not to be optimal. Remote sensing technology is now almost a quasi-mandatory way of investigation if a spatial and temporal context is required. How, in 7 years, did we pass from the ''tool without application'' status to the ''mandatory tool'' status? Four main reasons explain this shift: (1) proliferation of new sensors and data for direct and indirect sensing of the reefs; (2) proliferation and improvements of analytical, statistical, and empirical approaches; (3) recognition of global climatic change and human-induced lethal impacts on reefs; and (4) better integration of remote-sensing technology into the conceptual design of coral reef investigations.

In the last 7 years, roughly since the 8th International Coral Reef Symposium (ICRS) meeting in Panama in 1996, the generic tool ''remote sensing'' has gained a wider acceptance in studying coral reef processes for fundamental or applied objectives, with the emergence of new capacities (e.g. operational Sea Surface Temperature monitoring, Strong et al. 1997). Since 1996, both the data and techniques used for *direct* and *indirect* remote sensing of coral reefs have matured considerably. Direct remote sensing is when the reef itself is the target of the observations. Typically, benthic status (e.g. coral cover, coral bleaching extent), habitat mapping, geomorphologic structures, bathymetry, or water circulation are the desired information (Mumby et al. 1997; Hochberg and Atkinson 2000; Andréfouët et al. 2002; Stumpf et al. 2003; Isoun et al. 2003). Direct remote sensing is exemplified here with nine papers (Andréfouët et al. 2004; Brock et al. 2004; Elvidge et al. 2004; Hedley et al. 2004; Hochberg et al. 2004; Joyce et al. 2004; Karpouzli et al. 2004; Naseer and Hatcher 2004; Purkis and Pasterkamp 2004). Conversely, indirect remote sensing senses the environment around the reef, which can be the ocean (e.g. temperature, wave height, sea level, turbidity, or chlorophyll and colored dissolved organic matter concentrations), the atmosphere (e.g. aerosols, rain, solar insolation, or cloud cover) or the nearby lands (e.g. vegetation cover, watershed structure, or urban growth). It describes the boundary conditions of the reefs, as input or output of the reef system. The environmental patterns detected are then empirically or analytically related to processes occurring on the reefs themselves to confirm or build hypotheses (Abram et al. 2003; Andréfouët et al. 2002; Hu et al. 2003; Liu et al. 2003). Six papers of this issue have targeted the environment of the reefs to understand patterns in coral bleaching (Berkelmans et al. 2004; Woolridge and Done 2004), coral spawning (Penland et al. 2004), sediment transports and export (Acker et al. 2004; Ouillon et al. 2004), and dissolved organic matter transport (Otis et al. 2004).

The first obvious reasons to explain the renewal of interest are the many improvements in technology and practice: improved spatial resolution (direct remote sensing at meter-scale resolution, and indirect remote sensing at kilometer-scale resolution); and improved spectral discrimination (optimized band selection or hyperspectral data), appropriate temporal resolution (weekly or on-request direct remote sensing, and daily indirect remote sensing). In addition, systematic spatial coverage, longer coverage, plus concentrated efforts put into sensor calibration by space agencies, and complementarities between space missions have been critical factors to allow for comparative studies in time and space. The study by Acker et al. (2004), which requested observations shortly after hurricane impacts, would have been impossible without the daily coverage provided by SeaWiFS data. The 1998–2002 comparison of coral bleaching events by Berkelmans et al. (2004) benefits from the long-term and large-scale coverage provided by the AVHRR sensors from which sea surface temperatures (SST) are computed. Penland et al. (2004) use insolation climatology derived from various space missions to capture the timing of spawning events. Elvidge et al.'s (2004) coral bleaching detection would have been impossible without the capacities to order high-resolution commercial data with short notice.

Methodologically, large-scale remote sensing data for indirect remote sensing are often used to compute biophysical variables without algorithmic refinements specific to reefs. This comes at the price of some uncertainties and assumptions that need to be clearly stated (e.g. the 3D structure of neritic sediment plume in Acker et al. (2004), or CDOM concentrations just above the reefs in Otis et al. (2004). Patterns visible in large-scale products have their own limitations and are not necessarily reliable around reefs. Current research related to the use of indirect remote sensing focus on the definition of empirical, yet effective, proxies useful to forecast some type of reef processes. Analytical products such as SST are analyzed statistically to derive proxies that forecast bleaching events (e.g. the ''Max3d'' proxy in Berkelmans et al. 2004). These proxies are themselves used for empirical modeling and reasoning (Woolridge and Done 2004), highlighting another way to use remote-sensing products at the end of the processing chain.

The direct remote sensing papers are different. The goal is a better description of the reef itself and generally the benthos status (e.g. Purkis and Pasterkamp 2004). Less frequently, water quality is the goal (Ouillon et al. 2004). Remote assessment of the nature and status of reef benthic communities is another major challenge. The authors have sought to use their images to unravel the convoluted processes, positive and negative, that happen on reefs at various time scales. In theory, the information required to decode the optical signal and describe the bottom or water quality of the reef is well known: knowledge of spectral optical signatures of biotic and abiotic end-members – coral, algae, sand, etc. (Hochberg et al. 2004); spectral differences between these end-members (Karpouzli et al. 2004); spectral mixing of spatially aggregated endmembers (Hedley et al. 2004); radiative processes along the water and atmospheric columns (Purkis and Pasterkamp 2004). That is the conceptually best approach, derived from physical principles, and previously referred to as ''reef-up'' approach (Hochberg et al. 2003). Unfortunately, there is still a long way to go before this deterministic approach will be fully operational and can be transferred to many users. Factors limiting the practicality of this approach are, among others, data calibration issues, lack of an adequate model, the extreme complexity of radiative transfer processes, and the heterogeneity of the real coral reef world and the waters they lie in. The ocean color community proved the validity of this concept for the optically simple Case 1 deep waters, but the operational capacities quickly fell apart in heterogeneous coastal environments (Acker et al. 2004). Alternate methods were needed in coastal areas, and there is still a lack of consensus on how to process ocean color data in these environments. Nevertheless, useful progress has been made through development of many algorithms (Ouillon et al. 2004; Carder et al. 1999).

The deterministic ''reef-up'' approach is not the only way for direct remote sensing. Even if it is conceptually not the optimal solution, the statistical ''sensor-down'' approach (Hochberg et al. 2003) has provided many useful products for reef science and management and will continue to do so, especially in using images with limited spectral and spatial resolution. This approach requires local knowledge on reef communities or structure, and image-specific statistics drive the interpretation of the data. Joyce et al. (2004), Naseer and Hatcher (2004), and Andréfouët et al. (2004) provide examples of this approach for large-scale reef mapping for Maldives and Australia, and to estimate the biomass of invasive algae on Tahitian Reefs. ''Reef-up'' approach also requires adaptation and methodological developments since many new applications are still possible. Brock et al. pioneer a new way to look at reefs remotely by quantifying the rugosity of different bottom types with LIDAR data. Elvidge et al. (2004) adapt change detection techniques for direct coral bleaching detection and show for the first time that bleached coral can be observed directly from space under certain conditions. Joyce et al. (2004) attempt to combine large scale in situ monitoring with image interpretation, pointing to the fact that in situ monitoring and remote sensing certainly need better interaction and protocols to be mutually beneficial.

Scientists now have access to a vast arsenal of methods. In addition, they have also understood the relative merits of different approaches and how to streamline them to reach a particular goal. Coral bleaching's disastrous consequences helped trigger the use of what is currently the best example of a suite of techniques to address a problem of planetary dimension. In this special issue, bleaching detection and forecasting is discussed at three different scales: community (Hedley et al.), reef (Elvidge et al.), and region (Berkelmans et al. 2004; Wooldridge and Done 2004). Despite this wide range, the papers are all clearly connected. Hedley et al. test by simulation if bleaching can be detected in the case of heterogeneous benthos using hyperspectral data and an unmixing algorithm; Elvidge et al. (2004) show with real multispectral data that it is indeed possible to detect bleaching but only under favorable circumstances. Their findings could be used to confirm SST predictions and to fine tune the SST-derived proxies (Berkelmans et al. 2004) which can be used for management purposes (Woolridge and Done 2004). Another type of streamlined integrated approach is provided by Ouillon et al. (2004), who address sediment transport and reef sedimentation. They explore the feasibility of combining remote sensing, in situ data collection, and modeling. Their positive results show the value of integrating remote sensing early in the design of an environmental study, especially at large scale. Explicit early integration of remote sensing data are also exemplified by Andréfouët et al. (2004) and Naseer and Hatcher (2004), with two examples of resource assessment studies that would have been impossible in a timely and cost-effective fashion without the use of satellite data.

In conjunction with the development of Internet communications, new sensors for direct and indirect remote sensing will continue to provide fast access to a whole range of variables useful to understand reef processes at various scales of time and space, help planning the collection of in situ data and ultimately the management of coral reefs. New and old methods must be combined with comprehensive fieldwork to enlarge the spectrum of applications that can be targeted. An adequate and early integration of remote-sensing technology in the design of many coral reef studies is strongly recommended by many of the here-presented 15 studies. They represent the range of scales, methods, and applications that in the next 10 years will continue to flourish and to improve our knowledge of coral reef ecosystems.

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