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Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space

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Abstract In 2001, the Millennium Coral Reef Mapping Project initiated a global compilation of 30-meter spatial resolution Landsat 7 ETM+ satellite images that provides unprecedented coverage of coral reefs worldwide. From this unique image data set, it is possible to create globally consistent map products to serve local, regional and global applications. The project has examined ~1,500 images to design a thematically rich (966 classes) geomorphological classification scheme used to interpret and map every single reef of the planet. Compared to previously existing databases, the maps provide greatly enhanced localization, inventory and spatial analysis of reef structures. Distributed as Geographic Information Systems layers beginning in late 2003, the map products, have been used for a variety of applications. We present an overview of the milestones of the project and the methods we followed to create the image archive and use it to develop geomorphological maps of the world's coral reefs. We also present preliminary results obtained for a variety of applications—namely reef surface quantification, establishment of marine protected areas in Papua New Guinea and Eastern Caribbean, reef condition assessment in the Caribbean, morphometric analyses of Maldivian reefs and geochemical budgets in French Polynesian atolls. We believe that many scientists and managers will use the data and maps in a variety of applications and that the dataset will become a lasting foundation for understanding and conserving coral reefs around the world.

Keywords remote sensing, mapping, geomorphology, Landsat ETM+

Introduction

Current coral reef science and management programs seek understanding or protection of ecological processes that can be presented along a continuum of complex ecological scales—from individual coral reef organisms to coral reef biogeographic regions (Hatcher 1997). Small spatial scales and lower ecological organizational levels can be studied repetitively using experimental procedures, in aquaria, mesocosms, and in the field. However, at the other end of this continuum, regional (or global) processes are often handled in a limited way, by scaling up from a small number of samples of sites within a region, without actually capturing the full range of features and processes occurring there. This can be described as a pseudo-regional or pseudo-global approach. Remote sensing technology offers the most efficient means to uniformly observe and characterize an entire region without relying on sampling and extrapolation.

For many regions, one of the most basic problems yet to be solved can be summarized in three questions: "Where are the coral reefs? How large are they? How are they connected with each other and the surrounding environment?" Providing accurate answers to these simple questions is a basic requirement for successful management. Whether estimating the state of reefs, estimating the risks that land-based or marine-based threats can cause to reefs, determining the monetary value of one region's reefs, or designing a network of marine protected areas—all require accurate descriptions of reef system spatial structures and properties including geographic location, size, connectivity, topology, etc.

There are now a number of remote sensing data sources that can be used to help answer these basic questions. One preliminary approach is to use existing global data sets at low spatial resolution (1-9 km) to make analysis simple (e.g. Stumpf et al. 2003). However, we believe that trying to observe reef structures "directly" (*sensu* Andréfouët and Riegl 2004) at a 1-km scale is a mismatch with the spatial scale of coral reef features—like trying to study the dynamics of a city like Miami or Paris with 100 km resolution data. Loss of information on reef spatial parameters increases rapidly as spatial resolution becomes more coarse (Andréfouët et al. 2002; Andréfouët et al. 2003a). Based on these studies, we believe that high

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resolution data (tens of meters) are absolutely required to accurately characterize reef structures, even for regional and global applications. Until now, a continuous regional/global coverage at very high resolution was not available to complement other observations currently existing for reef work. Our goal was to create this data set, to fill an important gap in our knowledge and to provide a coherent foundation that will serve regional scale reef science, monitoring and management applications.

In order to explain how we built this foundation, we explain the successive phases and periods of the Millennium Coral Reef Mapping Project that will lead to the final global map product. The objectives of these phases were:

- Period 1 (1999-2001): acquire global high resolution coverage of coral reefs using the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor with 30-meter spatial resolution.
- Period 2 (2001-2004): develop a globally relevant classification scheme to characterize, map and inventory coral reefs worldwide and create an original, globally consistent line of Landsat-derived products.
- Period 3 (2004 and beyond): distribute the "Millennium Coral Reef Maps" worldwide, generally distributed as Geographic Information Systems (GIS) layers.

We have just entered the last period, but this is already a very exciting one that justifies all the previous efforts. The demand for products from potential users is very high and we will discuss several applications of the first products released.

Period 1 (1999-2001): Acquire Global High Resolution Coverage of Coral Reefs Using Landsat 7 ETM+ and the Launch of the "Millennium Coral Reef Mapping Project"

The most recent of the Landsat satellites was launched 15 April 1999 carrying the Enhanced Thematic Mapper Plus (ETM+) sensor. The ETM+ sensor is the latest in a series of Landsat sensors, includes band continuity with the Thematic Mapper (TM) sensor, used previously in several coral reef mapping and resources assessment projects. Detailed specifications of ETM+ are provided elsewhere (Goward et al. 2001). This multispectral sensor provides images with 30-meter spatial resolution and 4 spectral bands useful for reef work (blue, green, red and near-infra-red bands). A single image covers roughly an area of 180×180 km.

Compared to TM data, ETM+ provides superior quality (radiometric and geometric). Further, the planning of the data acquisition opened fresh perspectives for coral reef assessment because offshore reef and island areas had been neglected in previous missions because of recording limitations. The Long Term Acquisition Plan (LTAP) of the ETM+ mission included, for the first time, all coral reef targets world-wide, referenced geographically by the location of their footprint along a grid of Paths/Rows (Arvidson et al. 2001).

Practically, the LTAP populated a daylight, substantially cloud-free archive of ETM+ images at the rate of ~250 images per day, from June 1999, until at least June 2003 (when the sensor started to experience problems). LTAP systematically targeted coral reefs across the planet, including both coastal reefs and offshore oceanic reefs. Priorities and rates of acquisitions were determined for ~1000 Landsat scenes by the Landsat Science Team after consultation of the widest audience possible. These ~1,000 scenes covered all the reefs inventoried in the ReefBase 3.0 database (ICLARM 1999).

Following a series of publications aimed at testing and comparing the capacities of various sensors for reef work (Andréfouët et al. 2001a,b; Capolsini et al. 2003; Palandro et al. 2003a,b; Hochberg and Atkinson 2003), in 2001 the Oceanography Program of the National Aeronautics and Space Administration (NASA) funded the "Millennium Coral Reef Mapping Project" at the Institute for Marine Remote Sensing (IMaRS) at University of South Florida (USF) as a research project. In 2002, as a parallel application project, NASA also funded the Earth Sciences and Image Analysis Laboratory, Johnson Space Center, to enhance the distribution and application of the Millennium products, and other NASA-generated data sets. The combined goals were to achieve the first high resolution globally accurate and consistent geomorphological map of coral reefs worldwide and promote and distribute the derived products to users in every region.

Since 1999, the LTAP and the Landsat 7 mission have successfully acquired thousands of cloud-free ETM+ images. However, the high cost of Landsat data (US$450/scene) even for scientific applications has restricted and considerably slowed the transfer of a complete set of good images to the scientific community. IMaRS, which was not given funding for purchase of large amounts of data, used a variety of NASA, public, and private sources to obtain the images. Acquisition by the project of at least one low-cloud Landsat image for each reef location worldwide was not completed until November 2003. As of June 2004, approximately 1500 images were acquired for the Millennium project (Fig. 1). Through a partnership with the SeaWiFS project at NASA (Robinson et al. this volume), this data set is now almost completely public (at http://seawifs.gsfc.nasa.gov/cgi/landsat.pl). However, potential users should be aware that this is only one possible data set, and that for a given site, it may not provide the best possible Landsat-7 image acquired by LTAP.

Period 2 (2001-2004): The Development of a Relevant Classification Scheme to Characterize, Map and Inventory Coral Reefs Worldwide

The Millennium products were primarily conceived for research topics that required better quantification and accuracy of reef locations and extents, and improved characterization of reef structures. The main pre-identified applications were: (1) evaluation of modern coral reef surface areas; (2) classification of reefs

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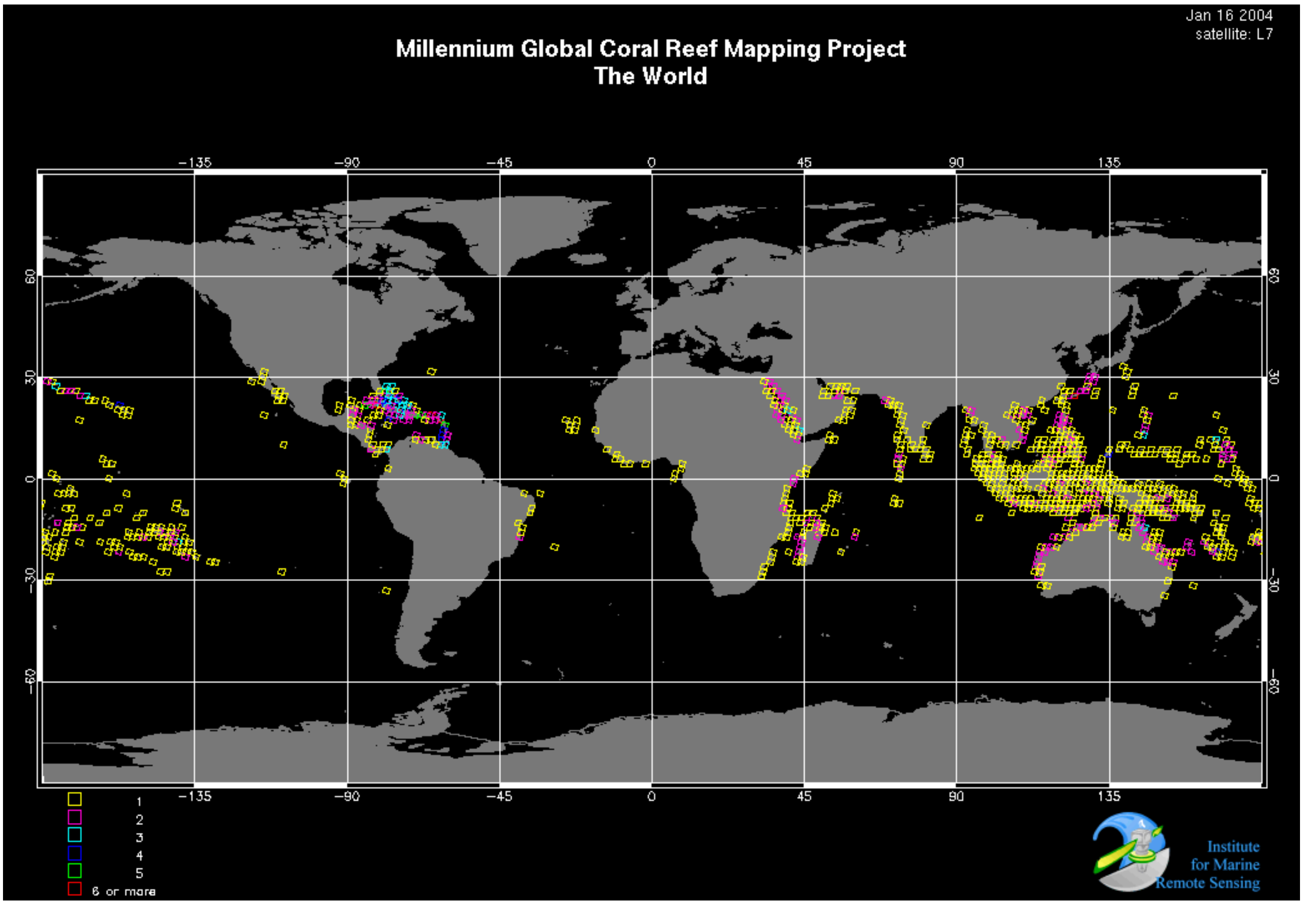

Fig. 1. Landsat images database available for the Millennium mapping project as of January 2004. Colors refer to the number of images available per path/row.

according to growth patterns; (3) assessment of the influence of reef geomorphological structure on biodiversity patterns over large geographical gradients; (4) evaluation of reef productivity; (5) assessment of the influence of climate and hydrology on coral reef growth patterns; (6) assessment of the influence of reef geomorphological structure on atoll lagoon functioning. However, the following items were added due to the strong demand from the managers or conservation organizations working on reef systems at regional scale: (7) planning for regional conservation; and (8) management of reef fisheries.

Before the mapping products could be made, a classification scheme for reef structures that would be useful for the above applications needed to be developed. This meant designing a relevant classification scheme, or, a typology of reef units that could be universally applied around the world. Several facts, considerations and constraints framed the creation of our classification scheme and mapping protocols.

1. The Millennium project created a new typology that was globally relevant because the existing typologies based on regional reef formation and development sequences (genetic schemes, e.g. Hopley 1982; Scott and Rotondo 1983) are based on few samples, and "*from imperfect and biased knowledge of the range and complexity of phenomena*" (Stoddard 1978). To avoid excluding any existing features, the new typology required examination of the entire continuum of reef structures worldwide, not in just a few regions.
2. We believed that a new reef typology, especially designed for global work, should follow Stoddart's (1978) principles: classes and labels should be explicit, singular, internally correct, not redundant, avoid radical redefinition and be comparable among different languages. Practically, this meant the use of existing well accepted terminology, but in some cases redefinition was necessary because variations in definitions for the same term (e.g. "atoll") are found throughout the literature.
3. All the information used to make the maps had to be derived from the Landsat 7 ETM+ imagery, and most decisions must be made using image-based criteria only since the field survey of all reefs of the planet was not an option. Although many sites are well documented with an abundance of literature, a larger number of sites are poorly described, such as in Indonesia (Tomascik et al.

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1997) or Red Sea.
4. We decided that classes would be geomorphological classes (as opposed to ecological or habitat classes) and explicitly labeled as such. Habitat maps are a desired product for several of the target research and applications areas, but unfortunately, habitat mapping is costly compared to geomorphological mapping because it requires significant field data for each location. Furthermore, Landsat, TM or ETM+, is not the best sensor for habitat mapping (Mumby and Edwards 2002; Capolsini et al. 2003; Andréfouët et al. 2003b). An explicitly geomorphological scheme is globally achievable and can still provide significant information relevant to conservation and biodiversity applications because physical structures can provide indications of the habitat present. Thus, we decided to add relevant complexity to the geomorphological scheme by explicitly accounting for exposure (to swell) and depth of reef structures. Indeed depth and exposure are two factors that strongly control habitat locations and development. By considering high, medium, low exposure, as well as deep and shallow sites, we provided the capacity to link explicit geomorphological classes with implicit classes of habitats which are, however, necessarily site-dependent.
5. The geomorphological classes should be relevant for the eight applications previously listed. When possible, we used key publications to identify the relevant classes for a variety of processes and sites (e.g. Adey 1978; Hopley 1982; Purdy and Bertram 1993; Scoffin 1993; Cabioch et al. 1995; Tomascik et al. 1997; Winterer 1998; Guozhong 1998; Adjeroud et al. 2000; Diaz et al. 2000; Kayanne et al. 2002; Kennedy and Woodroffe 2002; Cortès 2003) and then generalized them. The selected classes are relevant to identify key processes (e.g. climate or antecedent morphology controls on modern reef growth patterns) with their 2-dimensional (2D) morphometrics. One important consideration was how the Millennium products would be used in subsequent analyses. We anticipated that a typical approach would be a multivariate statistical analysis of morphometrics (i.e. surfaces, shapes and spatial topology) for the different reefs under investigation (Andréfouët et al. 2001b). The analyses could include ancillary information depending on the topics (fishery data, weather and climatology data, etc.).
6. We developed the classification scheme hierarchically in order to accommodate different applications. So, for example, the wide range of classes could be consolidated into "reef" and "non-reef," while another application might choose to use the full detail of the scheme.
7. To have maps suitable for morphometric analysis, smooth boundaries and solid polygons were needed. Noisy, pixellated products, as typically generated by automatic image classification procedures, would not have been suitable. Thus we relied on segmentation and photo-interpretation techniques to generate the regions belonging to the different classes. Those completing the mapping were trained with specific expertise in reef structure recognition for specific regions or reef types. Maps produced by different mappers are globally reviewed to insure consistency of the final products.

Based on the seven guidelines above, several temporary schemes were tested locally, between 2002 and 2003, for a variety of reef complexes. For these pilot sites ground-truth data and expert opinions (see acknowledgements) were also available (in Panama, Cuba, Mexico, Maldives, South Pacific Atolls, Great Barrier Reef, Meso-American Reef System, Mayotte, New Caledonia, Los Roques, South-West Madagascar, etc.) (e.g. Andréfouët and Guzman 2005). The classification scheme was finalized shortly after the global Landsat 7 coverage was compiled. Final products for the preliminary test areas were assembled and validated only after they had been re-mapped according to the final global classification scheme for the sake of consistency.

As in June 2004, the typology of reef units includes 126 reef geomorphological units, which are the branches in the hierarchical tree of the global scheme (Fig. 2). By associating depth, exposure, and whether the reef is continental or oceanic, with the 126 reef geomorphological units, we obtained 966 classes. All classes were identifiable using Landsat 7 data, segmentation techniques, and expert image interpretation of reef structures. Intermediate nodes in the hierarchy provided description at the levels of the main reef complexes (e.g. atolls, barrier reefs, etc.) and their sub-complexes (e.g. atoll rim, atoll lagoon, etc.). The detailed documentation and publication of the complete scheme is in preparation.

Period 3 (2004 and Beyond): Production and Distribution of the Millennium Coral Reef Maps Worldwide

Examples of Millennium Products

An example of a geomorphological map using the new classification scheme is provided for Ishigaki Island (Hasegawa and Yamano 2004), in the Ryukyu Archipelago, Japan (Figs. 3 and 4). Thirty five different classes (out of 966 possible classes) compose the classification which is of average complexity for this range of oceanic island size. It includes a variety of complexes with different exposure and depth: barrier reefs, coastal barrier reefs (defined in our typology as large fringing reefs with clear habitat zonation from shore to crest), fringing reefs and patches. These 35 classes reflect the complexity of the reefs around the island, and also illustrate the potential of a Landsat image in providing a rich thematic description.

Two regional products were shown during the 10th International Coral Reef Symposium: New Caledonia (Figs. 3 and 5) and the Maldives (Figs. 3 and 7). New Caledonia included 150 reef classes covering a total of 7,284 km$^{2.}$ It includes complexes of atolls, banks, barrier reefs, fringing reefs and patch reefs. Conversely, the Maldives included only atoll complexes, and were mapped using 23 classes covering 21,403 km^2 (or 4,844 km^2 without including deep lagoons).

Fig. 2. Hierarchical classification scheme used for the Millennium mapping project. Three levels are presented; the main division is between oceanic and continental reefs. Nodes (in italic) and blocks (colored) are the second and third levels in the classification hierarchy. The fourth level, not shown here, is made of 126 geomorphological units that enter in the composition of the different nodes and blocks. A block is typically made of a dozen possible geomorphological units. A total of 966 unique classes are thus assigned.

Fig. 3. Location of sites detailed in Figures 4 (Ishigaki Island, Japan), 5 (Ile des Pins, New Caledonia) and 7 (Central Maldives), and study sites mentioned in the text (Antilles, Kimbe Bay in Papua New Guinea, French Polynesia). World map from www.reefbase.org, with reef locations provided in orange.

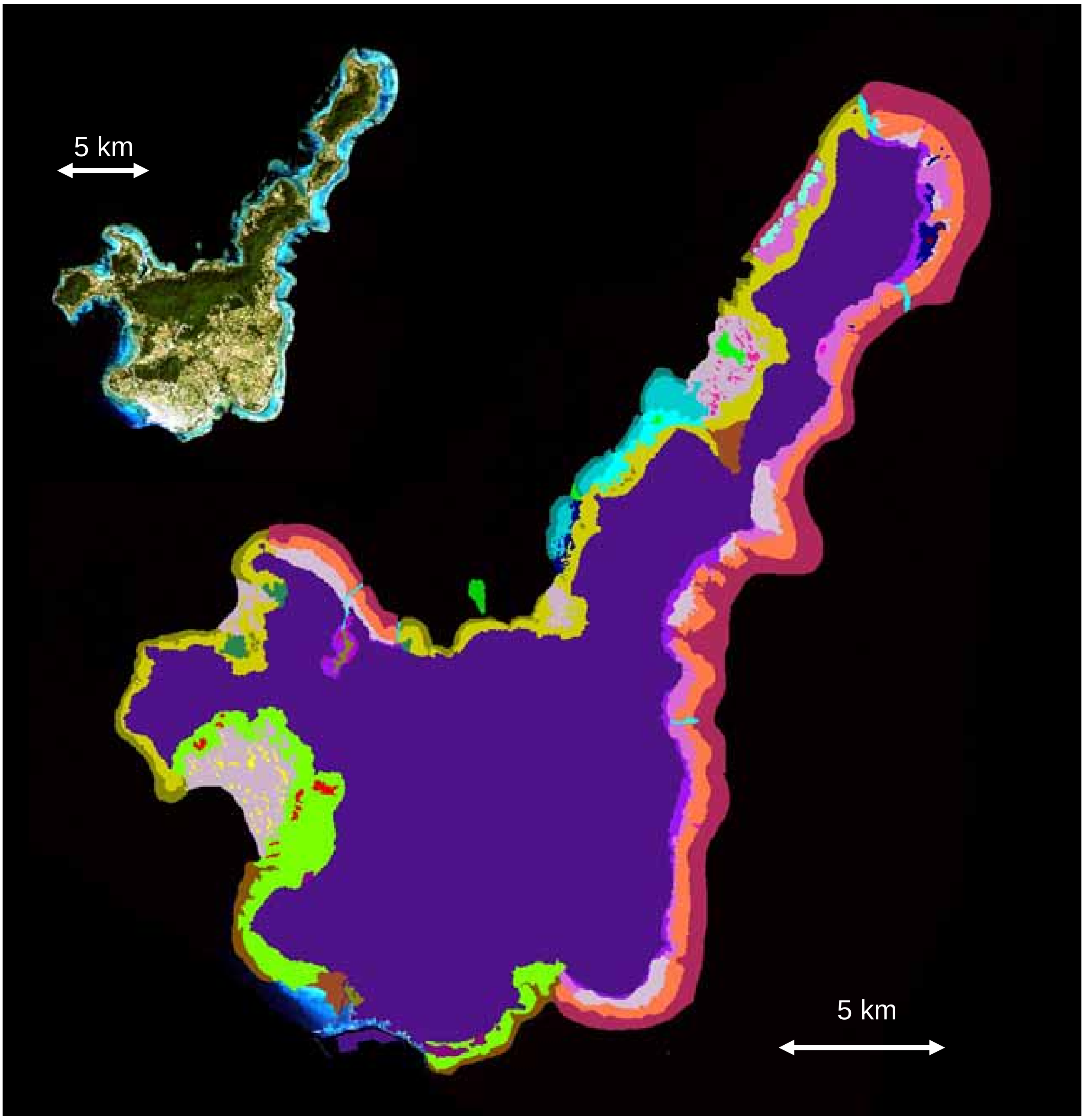

Fig. 4. Raw raster geomorphological product for Ishigaki Island, Japan (location provided in Fig. 3), with each geomorphological class in a different color. The source Landsat ETM+ image data is in the inset.

New Caledonia and the Maldives regional products are two examples that have helped identifying the limitations of the classification scheme. Millennium maps for New Caledonia were compared to habitat maps derived from high spatial resolution IKONOS (4 meters resolution) and QuickBird (2.5 meters resolution) satellite data. New Caledonia Millennium products failed to capture isolated small patch structures or dense areas of small patch structures, but this is inherent to the spatial resolution of the data (30 m), which implies that reefs smaller than 90×90 m are difficult to detect. New Caledonia fringing reefs in turbid waters (estuaries and bays) need validation by ground-truthing since omission errors occurred. In addition, even if reefs were detectable in turbid areas, several narrow fringing reef classes (forereefs, reef flats) could not be interpreted correctly due to the turbidity. Conversely, Millennium geomorphological classes could be used to predict the location of key habitats present on the outer barrier and coastal barrier systems, with good correlation between mapped classes and occurrences of seagrass/algae assemblages, coral, sediments and heterogeneous areas. These results obtained for a variety of New Caledonian sites will be detailed elsewhere in subsequent publications.

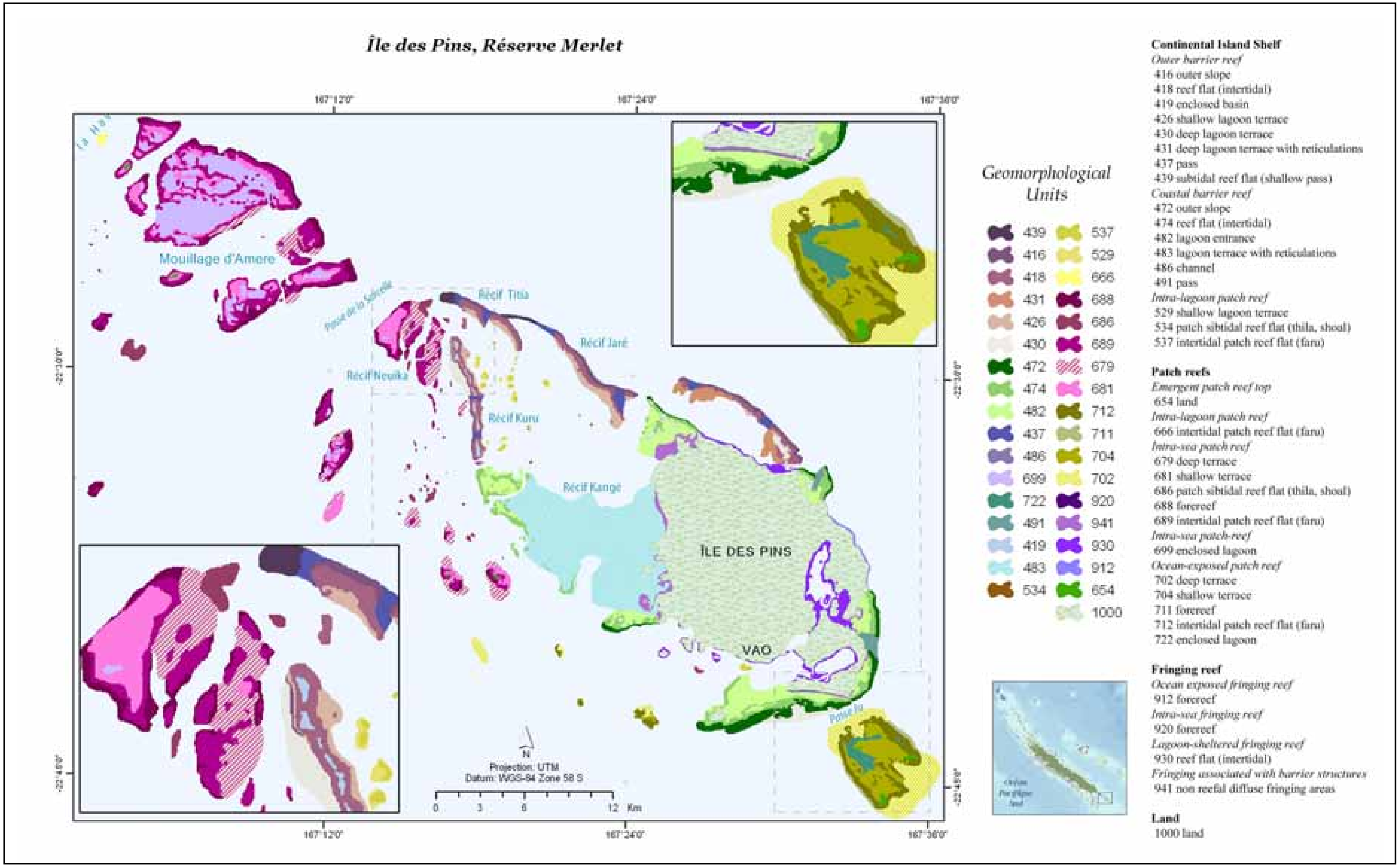

Fig. 5. Mapping GIS product and details of the geomorphological map of the South of New Caledonia (*circa* Ile des Pins, location provided in Fig. 3). Codes refer to the global classification scheme codes valid for any reef map worldwide. From the Atlas of New Caledonia coral reefs by Andréfouët and Torres-Pulliza (2004) modified by Julie Robinson.

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For the Maldives, comparison could be made with another mapping project based on Landsat 7 data. Naseer and Hatcher (2004) mapped all the atolls with typical supervised image classification and a mix of geomorphology/habitat classes. By interpretation of their classification scheme, we built a correspondence with the Millennium maps by merging several classes. For the classes that have similar or close thematic meaning in both schemes, we compared the surface of the classes and obtained very good match. For instance, total reef area is estimated at 4,285 km^2 and 4,092 km^2 by Naseer and Hatcher (2004) and the Millennium project respectively. Atoll rim reefs were 3,221 and 3,345 km^2 respectively. Lands (islands) were 227 and 237 km^2 respectively. This does not quantify the accuracy *per se* of the maps, but the good correspondence between the two different methods is striking for such a large regional assessment and increases confidence in the independently obtained, yet similar, results.

By late 2003, products were ready for delivery to several users for projects in progress that needed better reef maps or GIS data layers. Products were produced in two formats: raster products prepared for each Landsat scene (path/row designation) that could be tiled together, and vector products, delivered in ESRI (1998) Shapefile format. Shapefiles were either tiled by each Landsat scene, or mosaicked for the region of interest. Most users requested GIS vector products that were easily downloaded from the Internet due to their small size. There have been almost no requests for raster products. Some users have considered the products in their full thematic resolution, but most of them have merged the thematic classes hierarchically to create simpler maps. The products are complex to accommodate as many applications as possible and all classes are not necessarily relevant for a given application. We illustrate hereafter several of the applications presented during the 10th International Coral Reef Symposium made possible thanks to many partners (see acknowledgements).

A Preliminary Global-Scale Inventory Based on the Millennium Products

Millennium products makes possible the precise inventory of shallow water coral reef worldwide by merging all reef classes together to get a simple estimate of the total extent of the reef system. We compared the values obtained by the Millennium project with the previous global-scale references, i.e. the raster GIS data set compiled by the World Conservation Monitoring Center (WCMC) (Spalding et al. 2001). The WCMC data set was global, binary (reef-non reef) compiled from a variety of sources and nautical charts at different scales, digitized manually and resampled at 1km spatial resolution. WCMC data has demonstrated geolocation problems and many errors of omission. In contrast, Millennium products are also global, hierarchical and flexible, and offer 966 classes. They come from a mix of manual and automatic processing of one unique source of data at 30 meters resolution. They have the geodetic accuracy of the standard Landsat products (30-250 m), but have some limitations for small structures and turbid areas as discussed above.

Figure 6 shows “reef” extent for 128 sites worldwide, considering oceanic and continental sites separately. In the graph, each site or point is an island, an atoll or a significant stretch of continental reef (>50 km in length). Because of the lack of precise definition in the generic term “reef” used by WCMC (owing to variability in source data), two different configurations of merged Millennium classes were used for alternative comparisons. The first configuration includes “hard reef classes”—only the highly-productive areas such as reef flats, forereefs, and reticulated lagoons with dense construction. The second configuration, “hard and soft reef classes,” includes the previous “hard reef classes” plus all the other classes generally dominated by sedimentary areas (such as lagoons).

For Oceanic sites and for “hard reef classes”, the ratio WCMC/Millennium is 2.5, meaning that WCMC data statistically overestimated reef areas by a factor 2.5. For instance for Maldives, WCMC provides a value of 8,920 km^2, but we mentioned above that the real values are around 4,000 km^2.

Considering “hard and soft classes”, the ratio is 0.5, meaning that WCMC underestimates reef-lagoon areas in the second configuration by a factor of two (Fig. 6).

For Continental sites, both configurations are overestimated by WCMC. This is likely due to a widening effect of generally narrow (few hundreds of meters) fringing structures when resampling at 1 km resolution (cf. Figs. 4 and 5).

If we merge all the sites together (Oceanic + Continental), and generalize the results worldwide (a reasonable preliminary approximation since the 128 samples cover most reef configurations worldwide), we conclude that the previous global estimate of reef extent provided by Spalding et al. (2001) is overestimated by a factor 2.63 (configuration 1) and the area of reef + associated sedimentary areas is underestimated by a factor 1.85 (configuration 2). Considering “hard reef classes” (configuration 1), the previous global estimate of 284,300 km^2 (Spalding et al. 2001) would need to be corrected down to 108,000 km^2. These extrapolations will be updated soon with exact statistics for each region and country.

Current On-Going Applications of Millennium Products

By the end of 2003, Millennium products had been distributed to a number of projects as pilot data sets. Several products were distributed for local reef-scale projects; here, however, we explore only those applications with a regional character for several of the eight applications targeted by Millennium products.

Marine Protected Areas

A significant demand comes from governmental and nongovernmental agencies who are trying to establish networks of marine protected areas in order to conserve reef ecosystems using a variety of criteria (such as protecting maximum biological diversity, maximum

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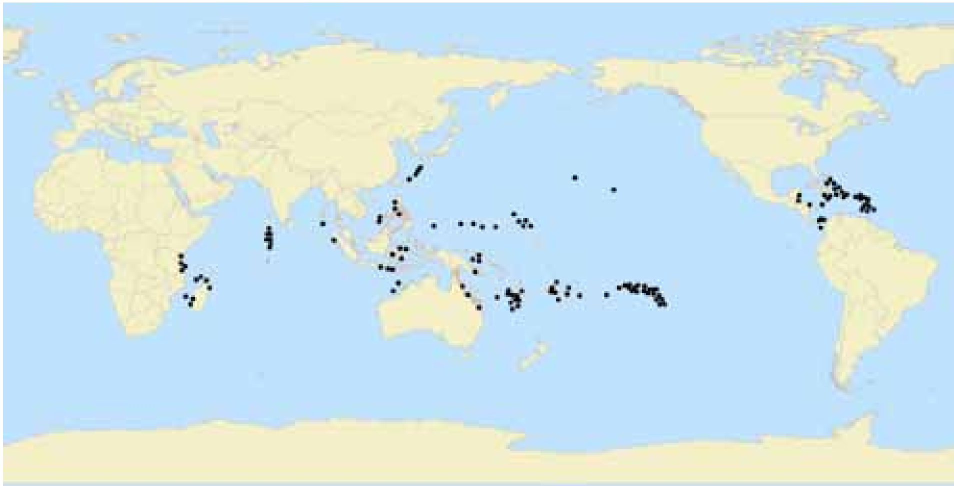
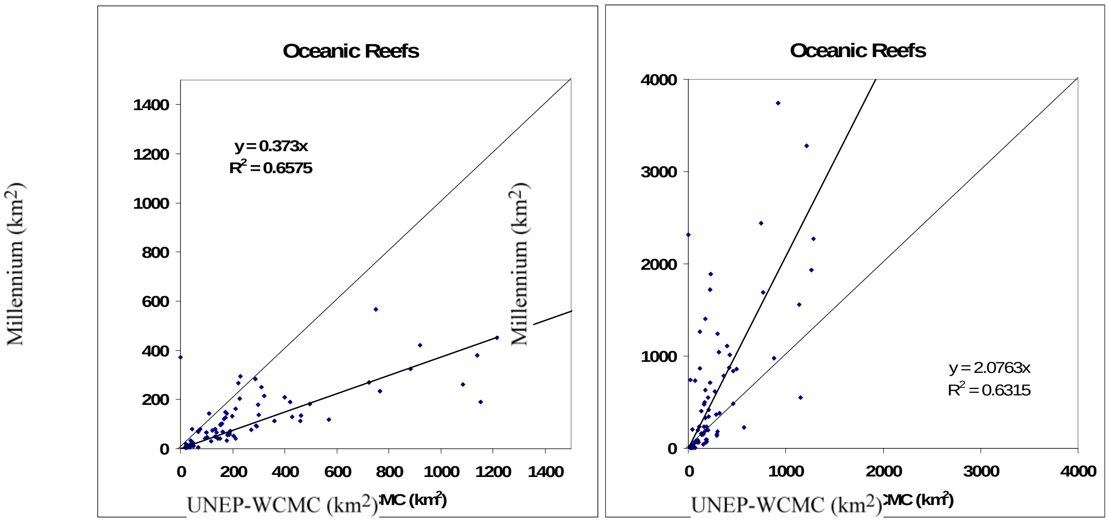


Configuration 1 (“hard reef classes”) Configuration 2 (“hard and soft reef classes”)



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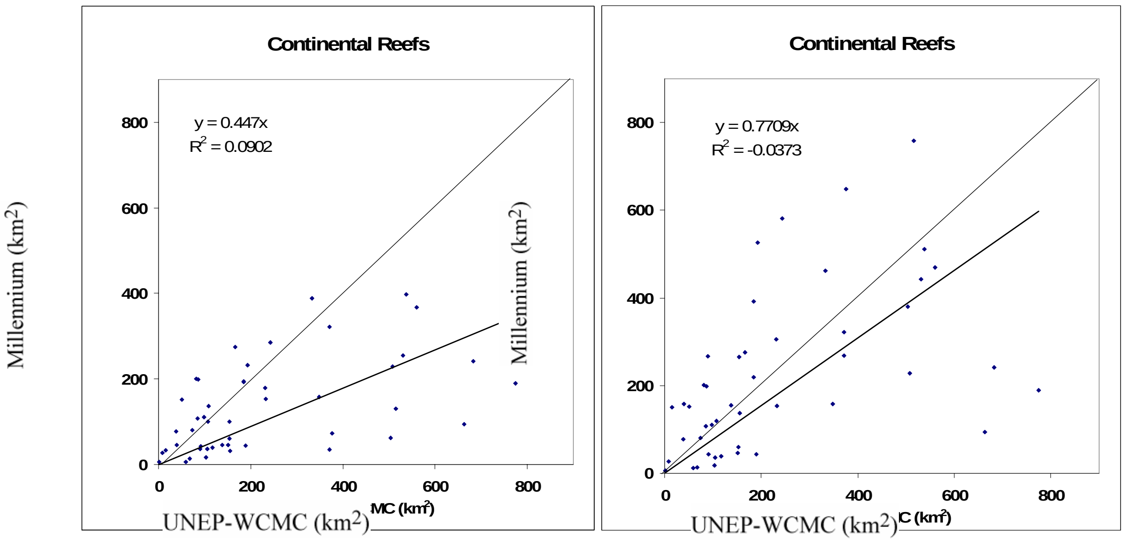

Fig. 6. Millennium quantification of reef areas (y-axis) for 128 sites worldwide, both oceanic and continental, compared with UNEP-WCMC estimates (x-axis). A site (data point) is an island, an atoll or a significant stretch of continental reef (>50 km in length). The line for a perfect correlation is also shown. “Hard” and “soft” reef categories are defined in the text.

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numbers of endemic species, a high percent of reef surfaces, etc). As such, detailed maps providing exact reef limits were needed. Products were provided to conservation organizations for the Caribbean (Lesser Antilles and Easter Antilles) and for Papua New Guinea (Kimbe Bay region) (Fig. 3) as one GIS data layer to incorporate in the Marxan reserve system selection software. Marxan has been developed to help solve the mathematical problem of selecting marine biological reserves based on biodiversity distribution, reserve sizes, and spatial relationships (Possingham et al. 2000). It is increasingly used in coral reef contexts and can be used to test a variety of reserve network scenarios.

In Kimbe Bay, Millennium maps have been used at full thematic resolution as one of the data layer serving the network analysis (Beger et al. this volume). They tested whether geomorphological classes could be used as surrogates for biophysical and biodiversity data (e.g. fish diversity) to assign conservation priorities to the different management units. The results from biophysical and biodiversity data sets were compared to results using Millennium maps alone or in combination with biological or biophysical data sets. Biodiversity data in Kimbe Bay suggested conservation priorities that were not reproduced by the Millennium products alone, but also were not produced by biophysical data. Geomorphologic structures were homogeneous for the Bay and were not useful for been discriminating among sites. Beger suggested a weighting of the different Millennium classes based on probabilities of occurrences of different habitats to better match the fish data constraints. She also noted that a sampling bias in biodiversity data is possible since fish data were not collected everywhere with the same quality.

To assign conservation priorities for the Lesser Antilles, The Nature Conservancy (TNC) (Kramer pers comm) ran a regional Marxan analysis where Millennium maps (merged at a simple hierarchical level) were combined with other freshwater and land habitat maps. The Marxan results show that islands with higher reef complexities were ranked with higher conservation priorities. TNC estimated that Millennium products were important for adding a regionally consistent high resolution marine coastal component that didn’t exist in the rest of the TNC data set.

From these two exercises, we conclude that detailed geomorphological maps are immediately useful for regional conservation planning. For local-scale planning, it is useful to combine the maps with other biological and habitat information as demonstrated by the Kimbe Bay case study, and to transform explicit geomorphological maps into explicit habitat maps.

Reef Condition Assessment

Recently, the report “Reefs at Risk in the Caribbean” has been released by the World Resources Institute (WRI) (Burke and Maidens 2004). It describes the level of stress that Caribbean reefs endure, including land-based pollution, fisheries pressure, natural exposure to bleaching, and hurricane exposure. The project handled a variety of regional data sets (land cover, soil erosion, watershed limits, fishery data, etc.) each with its own accuracy problems and constraints, and used several working hypotheses to combine all the data sets within a GIS analysis. The final product is a ranking of the risks to coral reefs across the Caribbean. For maps of reef location, WRI used a merged reef-non reef layer derived from the Millennium products for Panama, Honduras, Haiti, Dominican Republic, British Virgin Islands, Lesser Antilles, Turk and Caicos, and part of the Bahamas and Nicaragua. The rest of the Caribbean came from the WCMC data base and from NOAA (Puerto-Rico and US Virgin Islands). Updating the locations of coral reefs in the Caribbean, particularly for areas where they were not previously well-mapped and for small islands, improved the assessment of risks to reefs in the Caribbean (Burke and Maidens 2004).

Climate Forcing and Reef Growth

The following example illustrates how the Millennium products will be processed to assess the influence of antecedent topography and climate forcing on modern reef growth patterns and structures. Hopley (1982) has described the main processes defining the modern morphologies of the Great Barrier Reef shelf reefs. He demonstrated the validity of using 2D reef morphometrics to reveal the influence of the different processes, the history of the reefs, and to propose a genetic morphological scheme. We plan to use similar approaches elsewhere. For example, a morphometric analysis of Maldivian reefs (Figs. 3 and 7) was completed, focusing on the structure of certain reef types (faros and haas) located in atoll lagoons. Faros are ellipsoidal, intertidal reefs, and haas are ellipsoidal subtidal reefs well below the water surface. Purdy and Bertram (1993) have provided an analysis of the average orientation of the main axis of the ellipsoids to check the correlation with monsoon wind directions and test if modern reef shapes are due to weather patterns or due to antecedent topography. They averaged most of the lagoon patch reefs and worked at coarse resolution. Here, we improved the analysis by working at higher spatial resolution (¼ degree latitude and longitude) and by separating intertidal and subtidal reefs which are influenced differently by the winds. Prime orientations of faros are provided in Figure 7. The patterns differ from those identified by Purdy and Bertam (1993) because of the better spatial resolution. However, to fully finish the analysis, we need to measure the correlations between our morphometric results, rainfall, wind and swell climatologies, and existing sea-level and geology data explaining the large-scale context of the antecedent Maldivian platform.

Biogeochemical Budget

Finally, we provide an example of geochemical budget for the forereefs of 80 French Polynesia atolls, in the South Pacific (Fig. 3). Even if the role of coral reefs in the global carbon cycle is negligible (Smith 1978), reef biogeochemical behavior is a measure of reef health. Reef-scale, archipelago-scale or regional-scale estimates

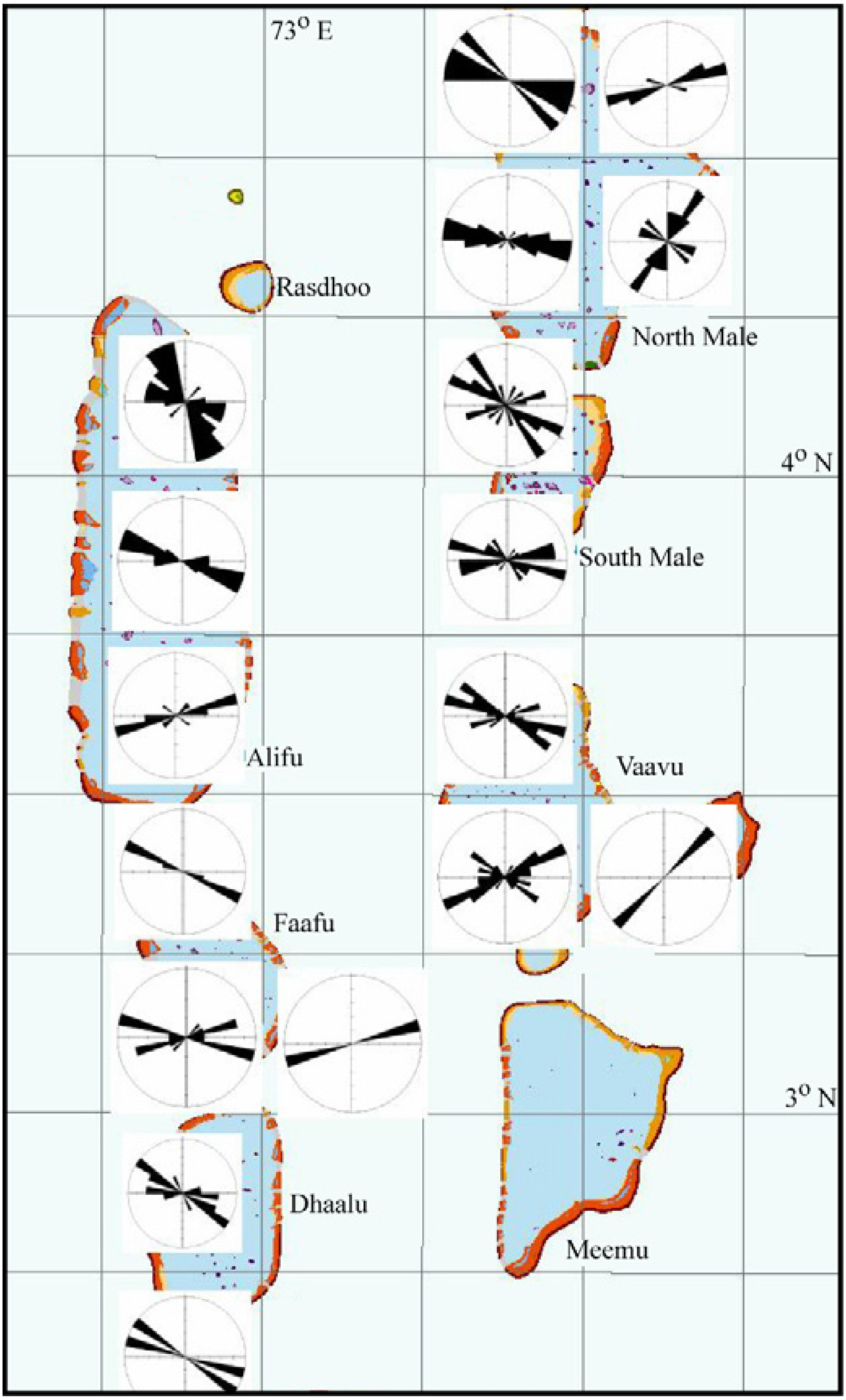

Fig. 7. Histogram of the compass orientation of the main axes of lagoonal intertidal reef structures (i.e., faros) in Central Maldives atolls (location provided Fig. 3), computed and averaged across ¼ degree of latitude and longitude and overlaid over a Millennium map of Central Maldivian atolls. Orientations vary widely, suggesting that different processes control local modern reef morphology, and not just monsoon forcing.

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can be used to compare reef intrinsic production capacities. Comparisons of current budgets between different hydroclimatic regions can be used to infer scenarios of changing reef conditions under dynamic climatic conditions. Geochemical budgets of reefs developing in marginal conditions (turbid waters, hot or temperate waters) can be used to forecast the future productivity of reefs that may have to accommodate a change in their environmental conditions.

Previous global models of coral reef calcification and production budgets have coarse resolution, (e.g. ~85 km^2, in Kleypas 1997). At such poor resolution, a spatial unit of the model includes the highly productive and calcifying areas dominated by reef-builders, as well as a wide range of other biomes, such as sedimentary areas, fleshy macroalgae and seagrass beds. Precise estimates in terms of areas and metabolic performances are required for the different reef zones (Vecsei 2004). Arial scaling up of metabolic performances is possible by combining high resolution remotely sensed images and standard calcification rates obtained *in situ* for different bottom-types (Andréfouët and Payri 2001).

In French Polynesia, the atoll margin generally comprises a narrow algal crest dominated by the crustose coralline algae *Hydrolithon onkodes* and a sloping outer platform dominated by corals (20-70 % coral cover in normal conditions) to a maximum depth of about 40 meters. Millennium products show that the total projected area of the margin system is made of 70 km^2 of algal crest and 434 km^2 of coral dominated outer slope. Uncertainties result from the deeper parts of the outer slope which cannot be consistently imaged by the satellite sensors despite clear oligotrophic waters. We therefore estimate that the total area of the margin ranges between 504 km^2 and 574 km^2 (horizontal projection). Previous estimates of $CaCO_3$ production by *H. onkodes* on Indo-Pacific and South Pacific reefs were consistent: 4.0 kg $CaCO_3$ m^{-2} y^{-1} (Payri 1987), 3.1 kg $CaCO_3$ m^{-2} y^{-1} (Chishlom et al. 1990) and 3.3 kg $CaCO_3$ m^{-2} y^{-1} (Chisholm 2000). Corrections based on the porosity and relief of the crest, for a horizontally projected area, led to estimates of 9.2-10.3 kg $CaCO_3$ m^{-2} y^{-1} (Chisholm 2000). For coral-rich outer-slope, a calcification rate of 4-8 kg $CaCO_3$ m^{-2} y^{-1} is applied (Kinsey 1985; Hatcher 1990). Simple computations for the 80 atolls suggest that the total carbonate production of the algal crests range from 644 to 721×10^6 kg $CaCO_3$ y^{-1}, and from 1,736 to $4{,}032\times10^6$ kg $CaCO_3$ y^{-1} for the outer slopes. Thus the total carbonate production is between 2,380 and $4{,}753\times10^6$ kg $CaCO_3$ y^{-1}.

Based on interpretation of Millennium Map products and published metabolic data, similar detailed regional budgets can now be constructed and are ecologically relevant to assess the relative role of different components in the productivity of a system (Birkeland et al. 1997). These budgets can be used in trophic modeling with production-limit conditions and can be used to extrapolate the consequences of climatic changes on reef productivity of other atoll systems.

Conclusion

From 1999 to the present we have worked through three development phases to create the Millennium coral reef products. For the reef science and management community, the NASA-funded projects presented here provide (1) an outstanding stock of reef images acquired by Landsat-7 at the request of the LTAP and available for purchase, (2) a global publicly available database of ~1,500 images, and (3) a series of GIS reef map products with continuous global coverage at high spatial resolution and hierarchical thematic richness to accommodate a large variety of applications.

Many projects led by a variety of institutions are currently using the Millennium products, or have requested products as soon as they are completed. Since the Millennium data set provides new ways to compare, assess and manage reefs, new analytical methods can be developed to take advantage of the full range of information. For regional work, multi-source spatial approaches need to be developed. Although the new methods may require use of empirical algorithms based on imperfect knowledge of the processes (McLaughlin et al. 2003; Burke and Maidens 2004; Wooldridge and Done; 2004), we expect that the combination of new products and new methods will generate better ways to study and manage reefs.

We hope that many scientists and managers will use these tools for their research and that these tools may become a lasting foundation for understanding and conserving coral reefs around the world.

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Web Sources

Millennium Coral Reef Project (IMaRS) *http://imars.marine.usf.edu/corals/index.html*

NASA Coral Reef Applications Summary and links *http://eol.jsc.nasa.gov/reefs*

Millennium Coral Reefs Landsat Archive *http://seawifs.gsfc.nasa.gov/cgi/landsat.pl*

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