this initiative to an *international* Ocean Atlas for coral reef environments. The website will display a number of standard environmental products (e.g. wind speeds, wave heights, solar radiation) but also develop and test new products which are especially relevant to coral bleaching. Outputs will (i) enhance the credibility of managers by providing timely spatial information (e.g. now-casting mass bleaching events), (ii) support reef research throughout the Targeted Research Working Groups, (iii) provide educational and research tools by defining the climatology of specific reef areas (iv) enhance understanding of climate change by recording and predicting environmental trends worldwide and (v) improve management of coastal watersheds through identification of water quality dynamics. An important aspect of this project is that the Ocean Atlas will be used by managers, scientists and students interested in many other ecosystems and parts of the World.

New sea surface temperature products, that predict temperature at sub-surface levels will begin in the first year of the project with principal development in Palau and Heron Island. However, the products will be tested and made operational in all project sites including Zanzibar. Solar products (short wave, PAR (photosynthetically active radiation), UV (ultraviolet light)) are planned for development in the second year of the project, winds in the third year, and turbidity in the fourth year depending on the availability of satellite data.

Coral bleaching is a major cause of concern for the future of coral reefs. The outputs of the Ocean Atlas will enable managers to monitor the larger scale severity of environmental stress in the coastal zone but do not easily predict which areas are least likely to experience conditions that precipitate mass bleaching. Physical models, based on hydrological and tidal information, show great potential for predicting how sea temperature will vary across a reef system given a certain amount of heating (i.e. which regions tend to heat up fastest and which remain cool). Such models will be developed and tested and after being merged with the outcomes of the "Bleaching Working Group", will enable managers to identify reefs which have a natural degree of resistance to coral bleaching and those that are most at risk. The creation of "bleaching risk maps" will be pioneered by NOAA in Palau, Heron Island and Puerto Morelos/Belize and collaboratively with the University of the Philippines at Bolinao.

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This project is part of a major initiative of the World Bank, with support of the Global Environmental Facility, to provide the best available scientific information on coral reef response to environmental disturbances and climate change. The "Coral Reef Targeted Research and Capacity Building for Management" project aims to conduct specific, targeted research to fill critically important information gaps in the fundamental understanding of coral reef ecosystems so that management and policy interventions can be strengthened globally.

Working Group on Remote Sensing

- Bleaching
- Connectivity
- Disease
- Modeling
- **Remote Sensing**
- Restoration

To manage coral reefs sustainably, practitioners and scientists require a vast array of spatially-explicit information. Spatial data are, for example, needed to design effective networks of Marine Protected Areas, monitor the health of coral reefs and provide an early warning system of major sources of stress. However, reefs are complex systems, affected by multiple natural and anthropogenic processes which operate across many scales. Remote sensing provides the only practical means to measure such processes and quantify their effects on coral reefs at meaningful and often large spatial scales.

Recent developments in remote sensing will enhance the cost-effectiveness of coral reef management. First, the cost of conducting many routine remote sensing tasks is falling because data are becoming less expensive and easier to manipulate. Second, and perhaps more importantly, the effectiveness of management will increase. Improved technology will allow several time-consuming management tasks, such as environmental monitoring, to be undertaken remotely, thereby freeing up staff and resources. Moreover, new technology provides fresh insight into coastal impacts and the vulnerability of coastal resources to such impacts. These insights enrich the knowledge-base for management, which, together with more detailed spatial information, will lead to better decision-making.

The Remote Sensing Working Group (RSWG) has orientated its research around four principal activities, each of which has a clear uptake pathway for improved reef management. Each activity is summarized below:

Creation of a decision-support and analysis software for monitoring the health of coral reefs using remote sensing

Until now, the remote sensing of coral reefs has been conducted on an ad-hoc basis with little consistency or general insight into its limitations. For example, we know that some aspects of reef health can be resolved on shallow reefs in French Polynesia but we cannot predict whether this would be a realistic expectation in say Jamaica, where reefs have a different flora and fauna, are located in deeper water, and where light penetration is slightly reduced because of higher suspended sediment concentrations in the water column. Without a generic understanding of the limitations of reef remote sensing, the technology may continue to be oversold or deployed for unrealistic management objectives, resulting in an inappropriate use of financial resources.

The RSWG will quantify the limitations of coral reef remote sensing by combining radiative transfer modelling and field experiments. Models predict the ability of a given remote sensing instrument to detect the subtleties of bottom reflectance that distinguish reef habitats or the cover of corals and macroalgae within habitats. Whilst the passage of light through the water column is relatively well understood, the interaction of light between reef organisms, many of which have complex structures, presents a research challenge. We address this problem using radiosity methods which were originally developed in the computer graphic industry. Coral structures are divided into thousands of individual patches, each of which behaves as lambertian reflecting surface. On reaching the reef, sunlight is reflected and scattered in predictable directions, from which we can calculate the net light recorded by the sensor once it has passed back through the water and atmosphere. Computer models will be refined and tested in the laboratory and then tested under field conditions in a unique, large-scale remote sensing experiment.

A series of platforms, approximately 3m by 3m in size, will be suspended at various heights above the sea bed. Objects will be placed on these platforms to represent explicit combinations of coral structure and various levels of reef health. Hyperspectral sensors will then be flown above the experiment allowing us to replicate the experiment under different levels of surface wind. The Rock Islands of Palau provide an ideal location to undertake this experiment under two levels of water clarity and with logistical ease. The experiment will also be carried out in Belize.

The development of coral reef radiative transfer models has several important consequences for both reef management and science:

a) Models will underpin a decision-support software to help practitioners match their management objectives to the most appropriate remote sensing technology and analysis (e.g. by entering the objective "coral cover in 10% increments" and the type of environment, principal coral species, depth, Secchi depth, etc).

b) The methods consider the problem of spectrally-unmixing the contents of individual pixels (i.e. the cover of corals versus algae within a given pixel). We know that the measurement of coral cover requires greater spectral information than is currently available from satellite sensors (hence our use of airborne techniques for experiments). However, the next generation of satellite sensors will provide cost-effective access to imagery of high spectral content (e.g. 200 bands) at a pixel size of ca 10-20 m. It is inaccurate to categorise entire pixels as a single substratum-type so sub-pixel scale methods are needed to tease out the composition of each pixel. Therefore, our research activities will prepare us for the next generation of satellites with a view to carrying out cost-effective monitoring of coral reefs from space. We will test the conditions under which hyperspectral data can be used to resolve the cover of living and dead coral on reefs in Palau, the Caribbean, and possibly the Philippines.

c) Modelling the reef light field will play a crucial role in bridging the gulf in scale between measurements of solar insolation upon whole reefs and the physiological response of individual corals to sunlight. We will be able to predict how a change in solar radiation would alter the light incident on individual polyps within a coral at a given depth. In time, such insight will improve the forecasting of bleaching impact by relating changes in solar radiation, measured by satellite sensors, to the physiological impacts upon corals. This issue draws together representatives from the RSWG and the bleaching WG.

Development of methods to detect changes in the coastal environment

The activities listed under section (1) provide tools to identify the habitat type and possibly predict the cover of corals and algae on a reef. These tools require high resolution imagery and direct field survey at the time of image acquisition and therefore have limited application to archived or low-resolution (30 m +) imagery. A wealth of satellite and photographic data are often available for reefs, sometimes archived as far back as World War II. We will conduct a number of activities to improve the way in which changes in reef condition can be predicted indirectly using remote sensing. These methods will highlight which areas of the coast have undergone the greatest change and help managers quantify the rate of change in reefal habitats.

Indirect changes in reef habitats will be detected using a range of spatial statistics that quantify the change in heterogeneity of reef reflectance over time (e.g. the Getis statistic). We will quantify the sensitivity of spatial statistics to real changes in habitat composition and potentially confounding events such as differences in optical water properties and depth. Three approaches will be taken to test the methods including (i) modelling spatial patterns of reef substrata and simulating changes, (ii) comparison of habitats within a sequence of images that have been intensively ground-truthed (Belize, Mexico, Philippines, Australia, Palau), and (iii) the acquisition of images before and after an acute disturbance event (e.g. bleaching event with high mortality) that occurs during the project lifetime.

The communication of coastal change can be difficult if using a map-based approach in communities that rarely use cartographic techniques. Previous work that made use of community based mapping and storytelling in central Java illustrated the difficulty that some cultures have with spatial constructs. Therefore, one component of this study will build upon change detection of environmental status and attempt to determine the best cartographic or narrative technique for communicating with local managers of coral resources.

Application of remote sensing to the inventory, monitoring and management of biodiversity

Recent remote sensing research has improved the detail of reef habitat maps but the interpretation and uses of these products for management has received relatively little attention. Specifically, what do habitat maps mean in terms of biodiversity and reef function and how should they be used for conservation planning? For example, many reserve selection algorithms require an extensive database of species' distributions which are costly and logistically difficult to establish. Remote sensing could largely replace intensive site-specific biodiversity surveys if the value of habitats as a surrogate for species (or functional) diversity were established in a variety of environments.

The World Bank/GEF Targeted Research project provides an unrivalled opportunity to taxonomic capacity within CoEs and quantify the ecological basis of habitat maps. The species composition of habitats will be surveyed in Belize and Mexico and compared assessed at a Caribbean-wide scale using comparable data from the Bahamas. Species will be identified for hard corals, macroalgae, mobile invertebrates, sponges (except those requiring spicule identification), gorgonians (except those requiring collection), reef fish (except gobies, blennies and cardinalfishes). Comparable surveys will take place in Palau and the Philippines but with less reliance on species-level identification. Emphasis will be placed on particularly important species (e.g. commercially-important or "keystone" species) but much of the species-level information will be replaced with functional, trophic categories. Whilst this compromise in detail does not resolve the species-level surrogacy of Pacific habitats, it is at least feasible and probably more relevant to the functional interpretation of habitats to management and ecosystem processes.

A second biodiversity activity will quantify the relationship between the topographic complexity of reef habitats (rugosity) and the relative density of reef fish. Habitat complexity will be measured using acoustic remote sensing methods and related to the density and biomass of around 30 ecologically and economically important fish species. Outputs of this research will enable managers to monitor the effectiveness of reserves effectively by stratifying their sampling by both habitat type and local habitat complexity, both of which affect the densities of reef fish. Maps of habitat complexity may also identify the location and extent of critical fish habitat which will guide MPA site selection and help understand the connectivity of fish populations (e.g. areas with high adult standing stock or high recruitment).

Creation of an Ocean Atlas and tools to manage coral bleaching

A wide variety of oceanographic and atmospheric remote sensing products are available for reef management but many are in disparate locations and user-unfriendly formats. A variety of US government agencies are establishing a national Ocean Atlas to collate a plethora of data sets relevant for coastal management within a single website. The RSWG will extend